THE EMERGENCE OF TOOL USE IN YOUNG CHILDREN

Een wetenschappelijke proeve
op het gebied van de Sociale Wetenschappen

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Preface

The chapters following present an approach of tool use from a perceptual point of view. The ability of young children to solve tool use tasks was investigated in order to identify the perceptual capacities that mark the shift from pre-tool use to tool use behaviour. The theoretical framework for this research is ecological realism as founded by J.J. Gibson.

It might come as a surprise for those who believe the mind to be a set of independent faculties, or modules, that tool use can be studied in a framework hitherto reserved for perception. If, however, human beings are viewed as developing organisms, in which action and perception capacities might develop in synthesis, one might discover close correspondences between the perceptual and action planning capacities.

For theories like Gibson's, the study of complex actions like tool use has not been the focus of attention. Primarily, Gibsonian realism has dealt with immediate perception-action couplings like posture maintenance and spatial orientation. However, complex actions need not, and should not be excluded from this approach.

In Chapter 1, the concepts of ecological realism are analyzed for their merits and shortcomings for the study of tool use. Where necessary, the approach is extended with new assumptions. In Chapter 2, from these a description of complex action in terms of nested actor-environment relationships is introduced. Two sources of complexity are assumed that affect the difficulty of perceiving the function of a tool. Experimental predictions regarding the difficulty of a tool use task are put to a test. In Chapter 3, the role of perceptual complexity in the development of tool use is studied.

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CHAPTER 1

Towards an ecological account of tool use

Towards an Ecological Account of Tool Use

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Introduction

In search of the roots of intelligence, we are led to the ability to use and make tools. Humankind is distinguished from other primates by the extent and variety of tool use. For archeologists, prehistorical tools are an important source of information about the capacities of their makers. From a psychological point of view, however, it is hardly known what capacities exactly are needed to use and make tools. Studies in which attention is paid to tool use as distinctive category of behaviour have been performed with primates by Wolfgang Köhler (1917). These experiments have been replicated with young children (e.g. Richardson, 1932). But these early studies have not been able to preclude that today, tool use is a field relatively neglected by psychologists.
A renewed psychological interest in tool use seems however to emerge from the ecological approach to psychology (Gibson, 1979; Reed, 1982; Noble, 1981). This approach takes the organism environment relationship as the starting point of investigation. In two complementary senses, tools embody a way of organisms adapting to their environment. An organism uses tools to make the environmental resources serve its needs. But also, the tool manifests the way in which the organism must tailor itself to environmental conditions.
The study of tool use diverges from the usual applications of ecological realism. It has dealt mostly with immediate perception action couplings, like posture maintenance and spatial orientation. The study of tool use necessitates us to deal with issues in which the organism realizes its needs not immediately, but by using environmental resources as means to an end. Because tool use in this sense is mediated action, in order to apply Gibsonian concepts some basic assumptions must be made which touch the foundations of this approach. These will be the subject of our present contribution.
The basic assumptions of ecological realism are already manifest in its name. Its concepts are embedded both in realism, by virtue of ascribing objective existence to

higher order perceivable invariants, and in ecology, by virtue of the belief that these concepts are to be defined in reference to the organism. This *relationalism* in the Gibsonian approach has been argued to be contradictory to its realism. As will be shown, the fact that the environment in tool use circumstances is not just *found* as a fixed entity, but also *made* by organisms, forces the issue. Confronted with the choice to give up either realism or relationalism, we chose in favour of the latter. This, because it is this assumption which in our view distinguishes Gibson from other, mentalist, conceptions of perception and action. We shall discuss the consequences of this step for the issues most relevant for the study of tool use from the perspective of ecological realism, viz. event perception and intentionality.

Relationalism vs. mentalism

In a mentalist approach to perception two distinct worlds are assumed: one outside the individual and the other inside. Strict borders separate these worlds, and each is described by its own exclusive set of properties, physical and mental ones, respectively. Physical states of affairs are regarded as meaningless; meaning is the realm of the inside world, to be described in terms of mental representations. Insofar as these are of perceptual origin, they are constructed from the meaningless sensory input by means of information processes. Because the physical world is the source of the energy that falls on the sensory receptors, there must be a stage at which the transition from physical to mental, from the meaningless to the meaningful, is made. Therefore, earlier, physical stages in the process are distinguished from later, mental ones. The former are called sensations and the latter perceptions. Fodor (1980) argues that the perceptual representations of the outside world have relations among themselves that could be understood without reference to the external world. A formal, syntactic theory of these representations could have an explanatory role for behaviour.

According to Gibson (1950; 1979) such a view is problematic, because of the cleft that separates sensation and perception. Its consequence is that meaning is the product of the mind. He wonders "If the solid visual world is a contribution of the mind, if the mind constructs the world for itself, where do the data for this construction come from, and why does it agree so well with the environment in which we actually move and get about"(Gibson, 1950, p. 13).

Gibson and those who follow his footsteps consider psychology as the study of "mind-world" relationships. But mind and world are redescribed in order no longer to be separate entities. The mind is part of the material world and its functioning can be understood only as situated within that world. It therefore comes as no surprise that

Gibson rejects the dichotomy between sensation and perception. Perception is not construction of meaning; meaning itself is determined by the physical structures in the environment.

In Gibson's terms, "perceiving is an achievement of the individual, not an appearance in the theatre of consciousness. It is a keeping-in-touch with the world, an experience of things rather than a having of experiences. It involves awareness-of instead of just awareness. It may be awareness of something in the environment, of something in the observer or both at once, but there is no content of awareness independent of that which one is aware (...) perception is not a mental act. Neither is it a bodily act. Perceiving is a psychosomatic act, not of mind or of body but of a living observer" (Gibson,1979, pp.239-240).

Therefore instead of mind and world, the interaction is described with preference by Gibson as one between organism and environment. The way these are described crosscuts the traditional boundaries between meaningless physical and meaningful mental states. Meaningful action is seen as changing the mutual relationship between an organism and his environment. Perception guides and controls action.

In order to specify how perception and environment are related, Gibson (1979) launches a program for redescribing the world of physics. Instead of descriptions of how light, or other forms of energy radiate from a single source, the focus is on the pattern of energy that radiates from several sources and is reflected by various surfaces. This pattern contains invariants that depend in a lawful way on changes within the environment. Invariants across transformations of the optic array specify texture and surface properties of objects in the world, including the organism itself or others.

Some of these invariants are relevant to a perceiver's behavior. These are called affordances. "The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill" (Gibson, 1979, p.127). Thus affordances are assumed to exist objectively in the structured array of ambient light. "The affordance of something does not change as the need of the observer changes" (Gibson, 1979, pp.138-139).

At the same time, affordances are specified as potential complementary relations between an organism and its environment. By consequence, affordances consist of body scaled information. Height of an object is specified in units according to perceiver's eyeheight. Thus action, viewed as the realization of affordances, is intimately related to perception: the affordances perceived have their counterparts in effectivities of the organism. Effectivities are the biomechanical characteristics of a body that allow certain actions. The body-scaled information is determined in relation to an effectivity. For instance, an affordance of an object could be "ability to be grasped". With respect to distance, body scaled here means that the distance is measured in units

of the perceiver's arm length, and size is measured relatively to the proportions of the hand. Other, well-known examples for criteria specifying a perceptual invariant relation between organism and environment are Lee & Reddish's (1981) study on plummeting gannets or Warren's (1984) investigation of stairclimbing.
Understanding perception within this framework implies to understand how action arises as a dynamic interplay between structural properties of an organism and those of the environment the organism is part of. The promise of such a research program lies exactly in breaking the boundaries of dualism in the mentalist way isolating the inner from the outer world.

Realism vs. relationalism

As has been recently noticed even in the community of ecological realists, there exists a tension in Gibson's work between his attempt to provide an alternative to the mentalist approach to perception in terms of a relational framework and the claim of realism. Some view this as only an apparent contradiction (Ben-Zeev, 1984; Heft, 1989; Noble, 1981), others as a sign of a fundamental one (Costall, 1986).
Ben-Zeev (1984) argues that whether affordances are to be characterized as objective or relational is a matter of levels of description. Affordances should be viewed as relational in a context in which a third person reasons about the world of appearence, and e.g. compares its ecological description to a physical one. For a first person, within a certain environment, however, an affordance may have a non-relational, independent existence as potentiality: "The affordances are always there to be perceived. The actual perceiver may or may not attend to affordances which, in principle, he has the capacity to perceive"(p.77).
According to Heft (1989), it is possible also within an environment, to reconcile the realism with the relationalism by distinguishing between actual and potential. Affordances are to be viewed as dispositional properties of environmental features scaled in reference to the action capacities of an animal. Whereas objectivity exists in specification of what is available to perception; its relational character is manifested in what is actually perceived within a certain situation.
Both authors agree that potentiality goes together with objectivity. It might seem that this aspect of the reconciliation of realism and relationalism applies without manifest contradictions to the study of tool use. A hammer, for instance has a variety of potentialities; it can afford hammering with but it could also, in principle be perceived as a lever or a means for reaching. The objective existence of the invariants that allow the detection of the tool function, the tool-affordances, could exist independently of whether in a situation they are actually perceived. What is actually perceived is

controlled by the needs of an organism (Gibson, 1975). These needs guide perception towards those environmental properties that may serve to fulfil it.

However, the contradiction between the objective and the relational character of affordances may become fundamental, if we stop taking the merely potential and the actualized character of affordances as isolated points in time. Costall (1986) attributes this insight to the American functionalists (Dewey, 1898/1976) in their combat against the "psychologist's fallacy". What a situation affords depends on the realizations of some earlier affordances; these may have changed the world and what it presently affords. In the unfolding of action the environment changes concurrently. Airplanes afford flying; they have been set into the world for this purpose. Before, there were, for humans, no affordances related to the act of flying. This implies that the ecological environment cannot be seen as a fixed entity with a fully determinate meaning. Instead, a genetic perspective on affordances is needed.

The realism that requires a predetermined fixed world on which individuals can act would make out of actors merely 'finders' of what already exists. A relational approach instead could treat them as 'makers' of their circumstances (Shotter, 1983). In human development, it is essential to describe how individuals evolve from 'finders' to 'makers' of their own situation. Costall (1986) therefore sees relationalism as the only way to deploy a genetic perspective of human perception and action. Actions are facilitated and constrained by environmental circumstances. These are created or modified by the agents. Tool use is a clear example for acting organisms as both 'finders' and 'makers'. Tools change the mechanical and/or perceptual capabilities of their users. They are used and produced in order to change objects or situations with respect to the needs of their users.

Tools themselves can both be "found" and "made". A stone used for breaking a nut is a 'found' tool. So is a stick, just picked up and used for termite fishing. At the moment a branch is broken off from a tree to be used as a stick, the tool could be regarded as 'made'. What is 'found' in this case are the properties of a branch as a potential stick. This includes the affordance of the branch to be capable of being broken off. Starting from these 'found' properties, the stick can be 'made' a tool.

A large variety of animals (fishes, monkeys, apes) use 'found' tools. Tool making is less widespread in animals, but known to occur also (Beck, 1980). Köhler (1917) reports how chimpanzees connected two sticks to build a new one, long enough to obtain the banana. This may illustrate that a genetic perspective on tool use might be useful also on an evolutionary time scale.

The same might apply to an anthropological study of tool use. People in a western society grow up in an environment full of very sophisticated and highly specific tool-objects. Under these circumstances, there is little need e.g. for children to make tools since for nearly all possible means specific tool-objects are available, starting from a spoon up to computers. In contrast, children growing up for instance in the countryside of Africa are confronted with what might be called the more "natural" world, one with much less objects ready for being used as tools. Since tools must be made on the basis of what is found, these children have to develop the capacity to detect properties that afford the making of a tool, in addition to those that afford its bare use. These children are forced to be 'makers' in their environment. For instance, three-year old children there are able to build well functioning birdsnares (Werner, 1953, p. 19).

In an ontogenetic perspective, the child usually first learns to use whatever environmental resources are found. Tool use, as mediated action, is a step towards increasing the action radius of the child. In our view, the first step is the use of found tools. Tool making, starting from whatever is found , is the next step in development.

The examples mentioned may show how 'finding' and 'making' are interdependent parts of the organism-environment interaction. Although affordances (of e.g. tools) could be regarded as 'found' only, this usually is not the whole story. For the study of tool use, we therefore need a genetic perspective, in which affordances are understood relationally.

Perceiving information for affordances

The consequence of adopting a relational account of perception is, that whatever information facilitates an action, specifies an affordance. This, because the objectivity criterion for affordances, that an affordance is fully specified by the invariances in the world, no longer can be used. Ecological specification has no other criterion than the corresponding action. Information as invariants from physical or geometrical properties in the world is not denied, its exclusiveness as a source for action however is. The information that specifies an affordance must be compatible with the invariants in the world. But a stronger relationship between invariants and information is no longer the rule.

In the literature on affordances, it is generally assumed that affordances are to be distinguished from the information for affordances (body-scaled information). "For example, a surface at a particular height may afford stepping-up on, and this property is specified by information; but it is the surface, not the information, that affords this action" (anonymous review). Affordances are 1:1 relationships between organismic and environmental structures. Information, in general is viewed as invariant of the objective world. The description of these invariances, however, is scaled in reference to the body of the perceiver. For instance, the height of an object is specified in units of the perceiver's eyeheight. (body-scaled information). Specifically, information for affordances is a 1:1 relationship between exteroception and proprioception. We maintain these distincions in our definitions. However, the implication usually associated with these notions, viz. that there is also a 1:1 relationship between exteroception and environmental structures as well as a 1:1 relationship between proprioceptive and organismic structures is herewith denied. Information must specify an affordance insofar as sufficient to act, but needn't determine it uniquely.

To illustrate the obsoleteness of unique specification of an affordance by information, envisage a frog capable of feeding itself by snapping at flies which it can visually detect. Surely, the ecological information for the frog consists of certain invariants based on physical energy patterns. But it is irrelevant whether the affordance corresponds to one physical energy pattern, uniquely characteristic of edible insects. It is sufficient that the affordance be reliable in most cases (not too many misses and false alarms), and it is necessary that the frog makes not too many dangerous misses and false alarms (e.g. snapping at a wasp). This shows that a unique state of affairs as such is neither sufficient, nor necessary, because what is really sufficient depends on the specific environment as a whole. If for instance a new species of insects would enter this environment that share the invariants of the edible ones but is dangerous, finer distinctions have to be made. Accordingly, the ecological information that specifies edible insects sufficiently, changes. Thus, focussing on the relation between organism and environment doesn't mean a reintroduction of subjective, mental representation but to the study of affordances in an adaptive or evolutionary perspective.

Body-scaled and object-scaled information

In the case of tool use, body-scaled information is not enough to specify the affordance of a tool. A stick can be used for obtaining an object because it cannot be reached. In this case, the absence, rather than the presence of the affordance "reachability" makes a tool out of the stick. The tool can 'effectuate' the reaching on the basis of properties complementary to those of the target. Thus *object-scaled information* is used to compensate the actor's lacking effectivity to reach directly. This object-scaled information in turn must be scaled to the actors body because he has to handle the tool. A stick which is long enough to reach the target but too heavy is useless. Affording to be a tool thus requires both, object-scaled information and body-scaled information. The interrelationship between object-scaled and body-scaled information could specify a *higher-order affordance*. It qualifies as an affordance, because the interrelation is body scaled information useful for realizing the goal of an action.

There is empirical evidence that object-scaled information is detected early in perceptual development in humans. For instance the relative size of two shapes which specify a containment relationship is reacted to by nine month's old children in habituation studies (Sitskoorn, 1991). That objects are scaled in reference to each other doesn't exclude the possibility that the whole scene can at the same time be scaled in reference to the perceiver's body. In order to actively put a small object into a container, the graspability of the object must be taken in account in order to act successfully. The organism's effectivities no longer have a special status as it comes to specifying what enables an organism to act; object-scaled information as well as body-scaled information are required for action.

Tools are always both body-scaled *and* object-scaled. For example, the screwdriver is object-scaled with respect to the screw. Its handle, however, is body-scaled to the user's hand and the required movement. Actions with tools must therefore be understood as based on the integration of object-scaled and body-scaled information.

Ecological realism so far has not been able to provide an appropriate treatment of these cases. Object-scaled information has been investigated as a perceivable invariant, but not as something the perceiver acts upon. For example, by using a technique based on Johansson (1975), Cutting, Proffitt & Kozlowski (1978) found that subjects correctly identified the sex of a person walking in the dark, with only a light bulb attached to the shoulder, and one to the hip. The *centre of moment* was the invariant which perceivers used for the identification, the cross section of an imaginary line drawn between the trajectories of the two moving light bulbs. Its position relative to the hip and shoulder was sufficient for making the required distinction.

Insofar as actions involving tool-like instruments such as tabletennis rackets have been studied, they are treated as mere effectivities, as if they were bodily parts (Bootsma & van Wieringen, 1990). Such an approach could be maintained as long as the selection of an object for the sake of its tool function is not the subject of investigation. But as soon as the issue becomes how someone could recognize a racket as a means for playing table tennis, the combination of body scaled with object scaled information becomes the matter of interest.

Events and object-scaled information

Object-scaled information has been studied in ecological realism under the heading of *event perception*. The role of the organism within an event, however, has been entirely viewed as that of observer, not as that of an active participant. As we shall argue, if the distinction between what is relevant in action and what is relevant in corresponding event perception could be overcome, we may claim that determinants of event perception should also be relevant if the observer himself becomes an active participant in the event.

In order to apply the notions developed in the context of event perception to tool use, they will have to be purged from their objectivist connotations first. This means taking seriously Gibson's proposition that "Ecological events, as distinguished from microphysical and astronomical events occur at the level of substances and surfaces"(Gibson, 1979, p.93). Events are characterized in terms of changes in the optic array. Three kinds of change are characteristic of events: changes in the layout of surfaces, changes in the colour and texture of surfaces and changes in the existence of surfaces. Because the mechanical tools used in psychological experiments with children typically cause changes in layout of surfaces, we will restrict the further discussion to this type of event.

It is undeniable that changes of layout are always mechanical events caused by forces. They are perceptually available through motion. Motion is detectable, because it brings about changes in the optical array. In optical terms, the reflections from illuminated objects in their complex patterns of interference shape the optical array. In geometrical terms, the positions of the objects known through their Cartesian coordinates in space determine their location in the optical array. These were assumed to be a specification of something. However, the exact physical or geometrical nature of these specifications was already considered irrelevant to the description of the optic array in perception by Gibson (1979). Regarding optics: "The two kinds of "motion", physical and optical have nothing in common and probably should not even have the same term applied to them. The beginning and the end of the disturbance in the light correspond to the beginning and the end of the event in the world, but that is about as far as the correspondence goes" (p.103), and regarding geometry: "The displacements and turns of detached objects can be classed as changes of layout because they are rearrangements of the furniture of the earth, not pure translations and rotations along and around the three axes of Cartesian coordinate space" (p.97).

Thus, by assuming a connection with physics, but opting out as a specification of this connection, the ecological description of the world is reducible in principle, but not reducible effectively to a physics description. This already comes very close to our claim that the Gibsonian specificity is redundant and therefore the physical description of the event should be treated as a constraint instead.

Important characteristics of events, such as causality, could already be reliably be detected with very impoverished stimuli, provided that some essential properties of these are preserved (Johansson, 1975; Michotte & Thinès, 1963/1991). It is of importance that these essentials in the organism-environment relation are described without having to depend on their physical structure. By this, the level of ecological description of the environment becomes a species of phenomenology. Such a phenomenological analysis has two necessary ingredients, it must be able to specify the units of the domain under analysis and what relations they may enter.

Units

Those units must be indicated within the ecological field of the event, which are sufficiently specific to enable an action. Action can be described as "that aspect of human activity in which people make a difference in their environments" (Shotter, 1983, p. 32). Correspondingly, units of an event can be signified by discontinuities in the flowfield. Discontinuity in the stream of information principally indicates the structural distinction between events or episodes within an event. As Gibson 1979 argues, "rupture occurs when the continuity fails, and this is a highly significant ecological event...The maximum of disruption can be thought of as disintegration" (p.102). So our assumption that the units of events are signified by discontinuities in the flowfield is in accordance with Gibsonian thought.

But, according to Gibson, what units are assumed in perception depends on the situation. "What we take to be a unitary episode is (...) a matter of choice and depends on the beginning and the end that are appropriate, not on the units of measurement"(Gibson, 1979, p.101). If e.g. the perceiver's goal is to differentiate between a walking or a standing person, stretching-relaxing can be seen as a unitary event, not a sequence of events. A repetition of this event characterizes walking. In the context of the perceiver's task no more detailed specification in terms of sub-events is needed. By contrast, in e.g. ball kicking, the precise amplitude of stretching is of importance. Therefore the unitary events should be the stretching episode as distinct from the relaxation one. A consequence of Gibson's claims about the situation-specific determination of units of an event is, that not a discontinuity as such indicates the borders of a unit, but the for an action in a certain situation relevant discontinuities.

Units are determined on the one hand from the perceivable discontinuities in the flowfield and on the other hand on the relevance of those discontinuities for an actor.

Michotte's phenomenology of causality

Michotte & Thinès (1963/1991) studied the structure of discontinuities in the stream of information as the basis for perceiving causality. In their approach, the perception of causal relations is taken as a phenomenon in its own right. Mechanical events like launching are investigated as ecological events, not just as sequences of displacements. Causal relations "include , in the usual sense of the word, the 'production' of a change by a preceding event, as for example, the reddening of an iron bar after heating, the displacement of a body after an impact, the various changes resulting from the motor activities of man and animals, such as pushes, pulls, compressions, launching etc" (p.66).

Michotte showed that causality was perceived in kinetic events on the basis of specific perceptual, rather than kinetic conditions on the configurations. These conditions were identified for perceiving the displacement of an object as caused by another: a form of transference of perceived motion that Michotte called ampliation. Entraining and launching are forms of ampliation. They produce the impression of causality regardless of real collision between the objects in the configurations presented.

The perceptual invariants that specify ampliation of movement are present in most of the mechanical and biomechanical changes occurring around us including our own bodies. "The conditions of formation of these structures are fulfilled at almost every moment of life, either after changes in the external environment or after the continuous movements of our body, of our limbs, and principally during all our manual activities"(Michotte et al., 1963/1991).

Michotte emphasised that the perception of those causal relations forms the basis for our understanding of events that we observe as well as of those we produce. "It is hardly necessary to stress that causal relations are essential to our knowledge of the world, since they seem to provide valid explanations of the changes that occur both around and inside us. Moreover, they allow us both to predict the occurrence of certain events and ultimately to control or adapt to them"(Michotte et al., 1963/1991, p.66).

In sum, discontinuities in the stream of information may qualify as units at a level that is relevant for acting successfully. That the relevance of certain units changes with the perceiver's purpose or skill and that therefore, they have to be identified relationally is in accordance with our view that there is no objective characterization of affordances.

Hierarchical relations between units

If ecological events are to specify the invariants of a tool, we must be able to indicate their distinctive phenomenal characteristics. Michotte, 1951/1991 studied the general characteristics of the so called "tool effect". In his experiments, he used e.g. an object which launched another one, and this one in turn launched a third object. We thus have a chain of discontinuities of the type which may qualify as the units of the events. An intermediary becomes activated by a "motor" and acts only because of that. Subjects attributed distinctive phenomenal qualities to the causal powers of the initial and the intermediary mover. "The intervention of the intermediary appears to be purely passive and dependent on the action of the motor object with which it is integrated as a constituent part; it is this which gives it a characteristic phenomenal aspect"(p.98).

Michotte thus could give an affirmative answer to the question whether "...the hammer manipulated by the user gives us a direct impression of being an intermediary, that is a means of execution, which is itself devoid of any initiative"(p.88).
The impression of an object as intermediary and passive depended on speed of motion and distance covered. With decreasing speed or increasing distance, the impression became weaker or disappeared. The intermediary object is then no longer perceived as passive but as self acting. Michotte describes the difference in impression as akin to "watching a billiard player launching a ball against another, which happens to be close enough that it could be grasped in the fingers (e.g., 1 or 2 cm away)" versus "observing a skittles game, where the ball travels a long distance before reaching the 'target'"(p.91). In the latter case the intermediary object is not longer seen as passive but becomes itself an agent of transmission. This may illustrate that the impression is constrained by the physical time structure.
Constrained, but not determined. The 'tool effect' is a phenomenon in its own right, not reducible to the physical properties of the discontinuities, like launchings, in isolation. This, because it is not their mere sequence that yields the phenomenal impression of an intermediate, but their manifestation as a hierarchically organized time structure. "...under certain conditions, the entire causal chain, as well as its internal dynamic hierarchy, is manifest (i.e., the exclusive activity of the motor object). In these cases the tool effect is an immediate datum, which is complete and open to view"(p.101).
Any event of some complexity will be interpreted in terms of interrelated cause-effect sequences. The causal structure of an event has got to be understood by imposing a hierarchy onto the causal chain induced by the units. Means-end relations may illustrate this, and specifically those including tools. No object properties in isolation make an object a means to an end; no properties in isolation make a tool out of an object. If a person picks up an object, takes it into his car and drives home with it, all this doesn't reveal the tool function of the object. But if once at home, he attempts to drive a nail into a wall by means of the object. The whole causal chain of events could be seen in retrospect as one unitary event involving tool use, viz. driving home in order to do a job. This illustrates that there is hierarchical structuring involved in the perception of tool function.

Action as event

Action can be regarded as the production of an event. The perceiving organism is involved, not merely as 'observer' but as 'maker' as well. Intentional action is producing an event, of which the final state was the desired outcome in the beginning. Thus intentional action requires the detection of the appropriate units of the event that allow control over the realization of the desired event outcome before and/or during the action. The units will therefore have to meet the constraints of physical reality.

Michotte sees a difference between observing a tool effect passively in an event and the case in which someone is involved in the event as the user of the tool. Here beside visual information, the tactile-kinesthetic information is a primary source. Michotte argues that the impressions of these senses are governed by the same structural laws as the visual ones. "These laws determine the degree of segregation of the tool in relation to the agent, the 'belonging' of the movement to the tool or the agent, the formation of a unitary activity, the internal hierarchy of perception, etc"(p.101). For the skittles mentioned above, he claims, "it is obviously 'me' who launches the ball, but it is no longer 'me' who knocks over the skittles but rather the ball that I had rolled in their direction....In fact, despite the duality of the actions, the player considers himself as the agent responsible for the result because he perceives 'himself' as the original source of the entire process"(p.102).

Michotte argues that the 'bodily self' should be considered as one object among others to be perceived. "It is natural that it should appear as the sole mover when we are using tools just as Object A (the 'motor' object) does in our laboratory experiments, and for just the same reasons"(p.102).

A tool user has the role of the 'motor' object. But for being an intentional mover, at least he has to be able to envisage the event he is producing at some level as a unitary whole. He has to perform an action on the intermediate, the tool, which in turn has to perform an action on the target object, caused by the users activity. Because in the end the tool's 'action' on the target realizes the goal of the actor, he has to able to see the nesting of causal relationships involved. This doesn't imply that he has to know all details of the structure of the event he is going to produce. The actor has to cause a series of discontinuities of movements that are specific to the intended event. These discontinuities signify the appropriate units. The amount of skill, or knowledge required depends on the amount, and structure of physical, mechanical, constraints one has to meet during action. As an example consider one of the simplest tool use tasks used originally by Bühler (1930) for 10-months old children. The task was to pull a string with a cookie attached to it. The event to be produced is the cookie moving towards the child. Just one change must be initiated, that from a resting target to a moving one by just one action, i.e. the pulling. Here, the body-scaled information of the 'pullability' of the string is sufficient for acting successfully. The child needs to be aware of the connection of the string to the cookie, but not of the exact nature of the connection. The object-scaled properties of cookie and string are irrelevant in this particular situation.

But if the string is not yet connected, this object-scaled information must be detected before the child can initiate the now much more complicated event of getting the cookie with the aid of the string. The event of 'connecting string and target' is a means to allow 'pulling' and in this sense is subordinate to it. The sufficient information for tool use now contains many more details. A nesting of subevents, discontinuities of a lower level, now contains the information sufficient in this situation. Since the first change of the situation to be initiated is given its meaning by the last one, an actor should be aware of a more deeply nested structure before he can begin acting.

The hierarchical structure anticipated of an action is continuously modified in a perception-action cycle. The 'tool-effect' demonstrated by Michotte shows how earlier information becomes reinterpreted in the context of later information. If we leave out the last of the two launchings, there is no impression of a tool if the first one is observed. If he intends to use a tool, the actor should have from the start the interpretation, an observer has obtained at the end of the event. But if, for instance, the action has unexpected consequences, he should reinterpret the situation in a manner similar to the observer's case.

Intentionality and action

An event of a certain complexity can sometimes only be understood by a distant observer in retrospect. For instance, a person leaves the room, comes back later with a chair and sits down on it. For an observer, the event as a whole can be understood from the end. For the person himself, however, the action was specified from the start by his intention to sit down, and constrained by the situation that there was no chair in the room.

This, intentional character of an action is taken into account in our description. Perceiving the event structure is necessary only if the individual act intentionally. These event structures should therefore be part of an ecological account of intentionality. Other attempts have been made to account for intentionality in the context of ecological realism. There are two principal lines to deal with intentionality within ecological realism. One aims at describing intentionality from the lawlike coupling between organism and environment (Kugler, Shaw, Vincente & Kinsella-Shaw,1990; Turvey, Shaw, Reed & Mace, 1981; see also Looren de Jong, 1991) and the other in terms of that what relates current to future action in a genetic perspective

(Shotter, 1983; Ingold, 1986). The first account is based on the realism in Gibsonian thinking and the second on relationalism.

The first approach deals with intentionality as that which directs action in a given situation. According to Turvey, Shaw, Reed & Mace (1981), intentionality is the mechanism that chooses among affordances to be realized. The actually perceived affordance in dynamic terms is described as the strongest *attractor*. According to Looren de Jong (1991), however, following the attraction of the immediately given in the environment is not an appropriate sense of intentionality, because directedness onto something not yet present cannot be dismissed from this concept. He prefers to speak of intentionality as "some kind of break-down of the direct nomic coupling between organism and environment, some dissociation where the organism supersedes nomological relations between behavior and environment, (...) characteristic of intentionality in perception (and, one might add, in action)"(p.97). As e.g. for tool making, and to a certain extent for tool use also, the object of intention is not immediately given, we must consider this approach the least promising as far as tool use is concerned.

The second approach deals with intentionality in terms of the relation between a previous perception and its further specification by performing action (see Shotter, 1983). Such a view has a relational character, since action is driven by experience, not by properties of the objectively existing world. This view has been clearly expressed in Searle's (1983) theory of intentionality. Ingold (1986) has emphasised similar views in an anthropological context.

Searle's relational theory of intentionality

Searle (1983) provides a relational theory of intentionality, compatible with our view, in which intentionality is described in terms of conditions of satisfaction. These are in many respects similar for perception and action. For perception, a condition of satisfaction for an intentional act is the existence of the object perceived. The visual experience of a table as an intentional act has the presence of the table as condition of satisfaction. In the same manner, the experience of an action has actual movements as conditions of satisfaction. The action itself is a presentation of the conditions of satisfaction of that intention. "And just as the visual experience is not a representation of its conditions of satisfaction but a presentation of those conditions, so I want to say the experience of action is a presentation of its conditions of satisfaction. On this account, action, like perception, is a causal and intentional transaction between mind and the world"(p. 88). In other words, intentionality is only realized within action when the perception of its conditions of satisfaction accompany the act.

Searle (1983) distinguishes between prior intention and intention in action. He calls a prior intention that which precedes action in the sense of anticipation of future state(s) of affairs or state(s) of the agent. For intention in action there is no such separation possible between intention and action because intention in action is equivalent to the experience of action. Consequently, prior intention is regarded as representation in the sense of a plan for action and intention in action as presentation.

The concept of affordances is in accordance with the concept of intention in action. Perceiving affordances means perceiving relational properties of organism and environment that afford action directly, i.e. without representations. Perceiving the graspability of an object is the intentional content of the action of grasping. The ecological event of grasping contains the condition of satisfaction for the intention of graspability. In the form of intentionality in action, intentionality is thus inherent in the *actual* perception of affordances (Reed, 1983).

Following Searle (1983), action is possible without prior intention, but there is no action without intention in action. Prior intention may cause an intention in action, which in turn causes the physical event that is the condition of satisfaction for the intention. Prior intention thus refers to a complex action as a whole (such as driving to my office). Once driving, the intention is carried out in action. Certain actions such as shifting the gear are intentional in action (they belong to the act of driving) but do not belong to the prior intention.

Although prior intentions are not necessary for all intention in action, Searle is inexplicit whether there are circumstances in which they are. Whereas no prior intention is needed in order to sit down intentionally when a chair is at hand, sitting becomes a prior intention when there is nothing in the room to sit on. It is necessary for going out and bringing a chair. Sitting as prior intention refers to the action as a whole. Sitting cannot be understood as intention in action for leaving the room, since this act doesn't contain the conditions of satisfaction for sitting. But the intention of sitting causes the intention in action of leaving the room.

Searle's prior intention as preceding action refers to a condition of affairs not yet present. A not yet existing state of affairs or goal, in terms of the affordance concept would mean that a possible, but not immediately realizable organism environment relationship that supersedes the immediately realizable ones. As an example consider grasping an object. A given situation may allow a realization directly. For an object within reach the actor may just perceive graspability specified by the relation between hand extension and object size and act intentionally without prior intention. But if the object is behind a barrier, the situation must be changed in a way that allows grasping. This requires prior intention. In this case attention must be paid to those invariants of the given situation that will enable grasping. Not yet present states of affairs subordinate to the original goal have to be anticipated. In the case of tool use, a relationship between tool and target that correspond to the tools function would be such a future state.

In our approach, the nested set of future states to be realized in order to reach a goal in a certain situation is given in awareness by the discontinuities in the event structure of the action. Because this event structure arises from the situation on hand, the intention is not a kind of plan in the sense of a map to read. Although perceptual specification of the situation on hand provide the direction for whether and how the goal will be realized (Shotter, 1983), it is not a specification of the action to be performed in the sense of a motor program. As 'maker' of an event one will produce *phenomenal* causality.

In human action, the actor himself causes phenomenal discontinuities. If the anticipated units of the event are compatible to the physical laws, the intended event will occur. Its phenomenal occurrence is the ecological event, not its physical occurrence. As actors we control phenomenal changes, not the changes in force fields that correspond to them. The phenomenal changes to be produced as a consequence of realizing affordances may be said to belong to the conditions of satisfaction of the intention.

Conclusion

The investigation of tool use within the concept of the Gibsonian ecological approach required an analysis of its potential for the description of complex action. Perception and action in this approach are studied as complementary modes of relating to the world. Perception of affordances enables action; through action the world is explored for perception. But the world cannot be regarded as an environment merely to be explored. Actors besides 'finders' are also 'makers' of their environment. People develop both by changing their perception and the circumstances to be perceived. Tools are a good illustration of this.

That people are to be studied as makers of their environment made us give up the objectivism in Gibsonian thought, in favour of an exclusively relational approach. As a consequence, the only criterion for identifying an affordance as a specification of a state of affairs relevant for action, is the *sufficiency* of this specification for enabling action and not its physical *uniqueness*. What is sufficient may depend not only on the environmental circumstances, but also on the skills of the perceiver. Since sufficiency of information is merely constrained, but not determined by physical conditions, it must be studied in its phenomenal specificity.

In our phenomenology, the information needed for using tools is both body-scaled and object-scaled. Affordances are usually studied in terms of body-scaled information only. Object-scaled information has been studied as event perception in ecological realism, but without an observer actively taking part in the event. Since action could be seen as actor-involving event, however, body-scaled information has to be combined with object-scaled information. A tool must be scaled to the body of its user and to the object to be worked on.

No isolated object properties specify an object as tool. Among the properties that make a tool out of an object, is its character of a means to an end. The phenomenal specificity of a tool as means results from the entire tool use event. The perception of a tool in its character as a means to an end requires the integral anticipation of an event structure that contains the causal means-end characteristics to be produced in using the tool. From Michotte's work on phenomenal causality we learned that a means-end relation is ascribed to a distinctive, hierarchically organized pattern of discontinuities. These characteristic discontinuities indicate the units of the tool use event.

Because a tool is a means to achieve a certain goal, intentionality is ascribed to the perception of objects as tools. We followed Searle's relational theory of intentionality. The discontinuities that correspond to the means-end characteristics of the tool use event could be seen as the conditions of satisfaction for the intention. Starting from Searle's definition of basic actions we argued that in the case of emerging tool use there must be prior intention that causes intention in action.

We have merely assembled the building blocks for a descriptive framework of tool use. We still are quite a few steps removed from an empirically testable theory. Some progress, however, could be made on account of our notion that tool use requires at some point in development a prior intention specified as a hierarchical structure of some complexity, of affordances. In order to test this account experimentally, we need on the one hand a rigorous definition of the complexity of the affordance structure, as a predictor for task difficulty and on the other hand an account of development in terms of what enables a developing actor to deal with increasingly complex affordances. We proposed solutions to these problems in relation to our experimental work (regarding complexity, see Van Leeuwen, Smitsman, & Van Leeuwen, submitted) and (regarding development, see Van Leeuwen & Smitsman, forthcoming).

The study of tool use thus led us to a revision of ecological concepts in a manner that touches on an on-going discussion concerning the relationship between ecological realism and Gestalt psychology (Natsoulas, 1991; Smith & Casati, in press; C. van Leeuwen, 1990a, 1990b; Zimmer & Körndle, in press). Starting from an empirical, 'theoretically neutral' issue we felt dismissed from a referee position and were able to approach the issues from a pragmatic point of view. A consistent approach to tool use was sought in a synthesis between the Gibsonian concepts with those of Michotte and Searle. It is possible that by doing so we reached a contemporary variant of a Gestalt position (van Leeuwen & Stins, in press). We might consider the present view applicable, in principle, also to other complex tasks, including social behaviour. Because our primary aim was stretching the scope of Gibsonian views, the issue of tool use already proved to be a litheness test for this account of perception and action. Certainly, the issue of tool use is a lithmus test for it as well.

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CHAPTER 2

Tool use in early childhood; perception of a higher-order relationship

Tool use in early childhood; perception of a higher-order relationship

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Tools are characterized by their subordination into hierarchically organized action. Perceiving a tool affordance requires the integration of several complementary relationships. In the case of tool use these include relationships between actor, tool and target. The integration is introduced as described by a higher-order affordance structure. On the basis of a recursive definition of the higher-order affordance structure concept, the difficulty of perceiving the tool function could be theoretically determined from the integrational demands of the complementary relationships involved in perceiving this function. Predictions were put to a test in three experiments, involving children aged between 9 months and 4 years. In a classical tool use task going back to Köhler, a desirable target had to be brought within reach by using a hook as a tool. By varying the relative position of the hook and the target, the difficulty of perceiving the tool function of the hook was shown to be in accordance with the theoretical description.

Introduction

The aim of this article is to investigate tool use from an ecological point of view (Gibson, 1979). Beginning in the second year of life, tool use could be regarded as a primary instance of complex action. The action radius of the child is stretched beyond the limitations of the body; a toy out of reach can now be retrieved by means of a stick. A striking characteristic of this newly emerged form of action, is that the stick is used as a means to an end. This should therefore play an important role in study of tool use as a distinctive kind of action. Most psychological studies however, do not focus on tool use in its own right, but merely use it as an instance of skill learning. From a motoric point of view, Conolly & Dalgleish (1989) studied how in mastering the manipulations of the spoon, the differentiation in grasping increases with age. Despite the detailed character of the analysis, their description did not distinguish the manipulations of objects as tools from other object manipulations. Yet, one year old children are able to handle a stick skillfully, before they start using it as a tool.

Tool use has been investigated from a *cognitive* point of view (Brown, 1990; Greenfield, 1991; Koslowski & Bruner, 1972). Koslowski & Bruner (1972) used tool use tasks to study the early acquisition of human problem solving. They described how a toy is obtained with the aid of a lever. Because a direct solution by means of reaching for the object would fail, solving the problem was assumed to require the "reorganization of the components of the situation into a detour structure, cf. Köhler, 1917" (p.797). The specific character of tools in solving such detour problems was not the focus of their interest. In their view behaviour is driven by an abstract representation, that conceives detour problems involving tools similar to those not involving tools.

Greenfield (1991) described tool use actions like eating with a spoon in terms of an action grammer. Tool use was described in analogy to the most advanced-level strategy children use for nesting three cups of different size into each other, viz. the *subassembly strategy*. Subassembly means that "two cups are combined to form a higher-order unit, which is in turn combined with a third cup to make the final structure" (p. 532). Cups can be nested by less advanced strategies, ones that "... involve only one level of combination: Two or more cups are combined in a chain-like sequence to make the final structure" (p. 532). Tool use tasks, however, can only be performed by a subassembly strategy, because of the hierarchic organization of means and end.

Although the complexity of tool use should also play a distinctive role for a Gibsonian account, this approach would be dissatisfied with complexity as expressed in an abstract action hierarchy, e.g. in number of items involved in a subassembly strategy. From an action point of view, the development of tool use shows integration of action. Integration is more than just nesting of increasingly complex structures. It also implies the smoothness, parallellism, etc, with which actions are assembled. In this sense, the ecological approach may be expected to go one important step beyond the subassembly-view. Besides the complexity expressed in terms of *number* of units in a hierarchy, also the *kind* of integration wil have to be studied in a unified framework. Moreovever, such an approach will give central importance to the role of perception for guiding action.

Tool use has been investigated from a *perceptual* point of view by Bates, Carlson-Luden & Bretherton, (1980), Köhler (1917) and Richardson (1932). Köhler (1917) in his famous primate studies showed the important role that the perceived spatial layout plays in the emergence of tool use. In a situation consisting of an actor, an object out of reach and a tool for obtaining the object, perceived spatial contact between object and tool was shown to facilitate tool use. Richardson (1932) applied Köhler's tool use configurations to children and obtained similar results.

Whereas spatial contact as such can be both useful or irrelevant, in these studies it was always useful. In other words, the spatial characteristics of the contact were not distinguished from their functional ones. Therefore these studies do not reveal whether perceiving the tool function is due to spatial contact as such or to its functional significance. Bates, Carlson-Luden & Bretherton (1980) suggested in their study with 10-month-old children that "primitive tool use involves knowledge of how two distinct objects can be used together in problem solving" (p.137). They argued that, when there is no spatial contact, anticipatory imagery is necessary to perceive the tool function. But also these authors didn't vary the functional significance of spatial characteristics.

Brown (1990) proceeded beyond the purely spatial characteristics of the configurations. She argued that the facilitatory character of spatial contact is due to "insightful learning and transfer on the basis of deep structural principles, rather than mere reliance on salient perceptual features" (p. 130). In her experiments, she showed that when spatial contact between target and tool was relevant for performing the task, like in Köhler's experiments, children quickly generalize tool use over surface properties of the configuration. This might seem in accordance with her view that a deep structure is involved. But for Brown, "deep" means "abstract", rather than functional for a task. In some of her conditions, however, she introduced another tool (a magnet), for which contact played no functional role. Here, generalization was much slower to occur. She used the fact that generalization occurred after all as an argument for the irrelevance of salient properties in the surface layout. But the difference in time needed to acquire the generalization in our view shows that those salient features sometimes do matter. Therefore, Brown's study illustrates rather the opposite of its conclusion, that the structures involved are not abstract, conceptual ones, but may be perceptual ones of a nature yet to be clarified. A theory should be able to pick out the perceptual factors that matter, rather than treat them as irrelevant variations.

Despite the fact that the above studies have addressed the issue of tool use from different viewpoints, they all seem to share a common assumption, viz. that the predominant source of difficulty of the tool use task is due to the difficulty of finding an adequate abstract representation (of a motoric, cognitive or perceptual nature).

A different view is suggested by the work of Michotte (1951/1991). He studied the so called 'tool effect', i.e. the direct impression of the functioning of a tool. His question was, whether "...the hammer manipulated by the user gives us a direct impression of being an intermediary, that is a means of execution, which is itself devoid of any initiative" (p.88). In his experiments, Michotte used an object that launched another one, and this one in turn launched a third object. Subjects attributed distinctive phenomenal qualities to the causal role of both the initial mover (the "motor" object) and the intermediary, which was perceived to be a "tool". "The intervention of the intermediary appears to be purely passive and dependent on the action of the motor object with which it is integrated as a constituent part; it is this which gives it a characteristic phenomenal aspect."(p.98). The impression of an object as intermediary and passive depends on speed of motion and distance covered. With decreasing speed or increasing distance, the impression became weaker or disappeared. Then, the intermediary object is no longer perceived as passive but as self acting.

According to Michotte, the 'tool effect' is an awareness, not reducible to the event's mechanical components, such as launchings, in isolation. This, because it is not their mere sequence that yields the phenomenal impression of an intermediate, but their manifestation as a hierarchically organized time structure. "...under certain conditions, the entire causal chain, as well as its internal dynamic hierarchy, is manifest (i.e., the exclusive activity of the motor object). In these cases the tool effect is an immediate datum, which is complete and open to view."(p.101). What Michotte describes as a hierarchically organized time structure for the perception of the 'tool effect', corresponds at an abstract level to the hierarchic organization in subassembly strategies for action as described by Greenfield (1991).

But in addition, Michotte emphasized regarding the relation of perception and action, that the perception of those causal relations is the basis of our understanding of the event we observe as well as of the one we produce. "It is hardly necessary to stress that causal relations are essential to our knowledge of the world, since they seem to provide valid explanations of the changes that occur both around and inside us. Moreover, they allow us both to predict the occurrence of certain events and ultimately to control or adapt to them" (Michotte et al., 1963/1991, p.66). Michotte thus suggests that if the perceiver of the event is also involved in it as actor, the phenomenal 'tool effect' that is available to perception is the same as the one that has to be produced in action. Thus, like Gibson (1979), Michotte assumes action as guided by perception; tool use could be performed optimally under permanent perceptual guidance. More importantly, perceiving a tool then depends on the ability to anticipate the complex causal event structure involved in tool use.

For Michotte, a complex, organized event structure can be immediately given in perception. Because we believe that if Gibsonian conceptions should be made applicable to complex actions such as tool use, a similar assumption should be made for it. In our next session, we shall therefore deal with the intricacies of applying the Gibsonian conceptions in this spirit.

Tools and affordances

Gibson (1979) and Shaw & Turvey (1981) have been arguing more explicitly than Michotte that perception is for action. The action relevance of perception is the detection of affordances. Affordances are potential complementary relations between an organism and its environment.They indicate how the world could be acted upon by the organism. For instance, an affordance of an object could be "ability to grasp". Thus action, viewed as the realization of affordances, is intimately related to perception: the affordances perceived have their counterparts in effectivities of the organism. Effectivities are the way the actor could use the biomechanical characteristics of its body to act upon the world.

A cornerstone in Shaw & Turvey's (1981) concept of ecological realism is the principle of duality of affordances and effectivities. Only those affordances make sense, to which a complementary effectivity exists, and vice versa. With this principle, they were able to dismiss the objection that the concept of affordance would exclude nothing and therefore be devoid of content.

In agreement with Shaw and Turvey's principle, we might regard the perception of a tool as a complementary relation between what the tool affords to the perceiver and what the perceiver can effectuate with the tool. We might also specify what the target affords to the actor. But in case of tool use the actor doesn't have the corresponding effectivities to realize this affordance immediately. Only by means of a tool the actor has the required effectivities for realizing the target affordance. This implies that realizing the affordance of the target involves not only a dual relationship between actor and target but also ones between actor and tool, and between tool and target.

However, by following Shaw & Turvey's approach strictly, the description of tool use would merely require that the complementary relations between actor and target, between actor and tool and between tool and target are described as dualities. Dualities could be described between actor and an Object 1, between actor and an Object 2 and between Object 1 and Object 2. But none of these dualities in isolation would pick out Object 1 or Object 2 as the tool and the other one as the target. It is essential for the tool that it combines properties that relate it to *both* the actor and another object in a manner that allows the actor to handle this object. What is meant is most clearly illustrated by the screwdriver. One of its ends is a potential complementarity with a screw (target object) the other is a potential complementarity with the actor's hand.

An object has no tool affordance irrespective of the target. Likewise a tool cannot be treated as a mere effectivity of the actor in the sense of Shaw & Turvey (1991). A stick already in the hand could be viewed as an effectivity of the actor. Even a stick on the floor could be viewed that way, if we assume that it is unintentionally picked up, and once picked up could be used. But in order to explain why a stick is deliberately chosen by the actor as a means to an end, the specific tool affordance of the stick has to be taken into account. Tool affordance (and effectivities) must be described as complementarily related to both, actor and target.

Higher-order affordance structures

The affordance of a stick as tool for retrieving a distant toy is built out of several possible complementary relations between physical properties of the tool, such as its shape, size, texture or mass, and corresponding physical properties of the actor's grasping system such as shape, size, force or accuracy of motor control. A stick can have a wide variety of affordances, which correspond to a variety of possible actions. Only a small subset of these affordances (and the corresponding effectivities) involve the stick as a tool. This subset is determined, among others, by the relation between stick and toy. Properties as shape, size, texture and mass of the toy in relation to similar, complementary properties of the stick determine, whether the actor can manipulate the toy by means of the stick. For instance, the stick must at the same time be light enough to be manageable (stick-actor) and strong enough to manipulate the target (stick-toy). At the same time the subset of manipulations is constrained by the affordance relations between actor and toy. These affordances correspond to the potentials to exert transformations on the toy. For instance, if the toy at issue is a tower of blocks and the actor has the aim of playing with an intact tower, its instability necessitates a minimal tolerable shakiness in stick use. Likewise, the relations between actor and target, as well as between tool and target are constrained from the respective remaining relationships.

We could describe the means character of an object as tool in terms of affordance structures by assuming a higher-order structure that describes the mutual constraints as dual relationships between tool and target, tool and actor, *and* target and actor. In order to state the interdependence of these relationships, maintaining the duality principle, we propose a concept of higher-order complementarities. Since an affordance of a tool as a means contains the proposed higher-order structure of complementarities we will speak of a higher-order affordance structure. With this notion, we implement a suggestion by Kugler & Shaw (1990), Cutting (1991) and Gray, Neisser, Shapiro & Kouns (1991) to extend the established concepts of ecological realism into still higher-order concepts, preserving their duality characteristics.

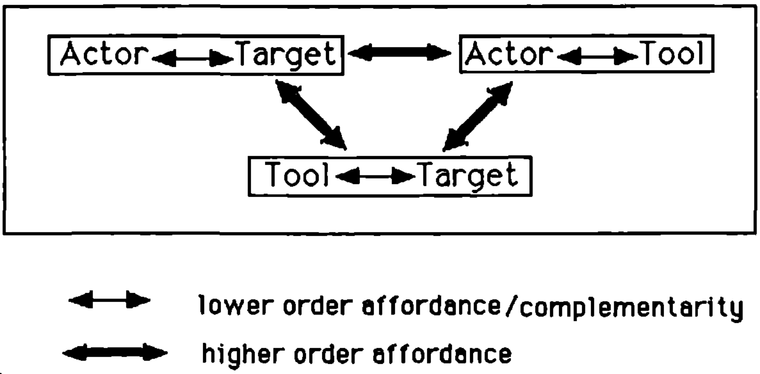

Figure 1: The relationships between actor, tool and target as mutually constraining complementarities in a second-order affordance structure.

When these structures are called (higher-order) affordances, this is because they contain body-scaled information. Body-scaled information is a consequence of the principle of duality. Affordances are described as a ratio of environmental and organismic properties, such as height of an object in relation to the observer's eyeheight. However, in the case of tool use, complementary relationships between tool and target are involved. An object-object complementarity obviously cannot be expressed in terms of ratios between organism and environment. Thus the higher-order structure to be perceived entails besides body-scaled information for the actor-tool and actor-target complementarities also information about object properties scaled in reference to each other, instead of to the body. Merely object-scaled information cannot be qualified as information specifying an affordance. Since an object-object complementarity must be realized by action, it must be complementarily related to an affordance at a higher-order level. Then, not a single object, but a complementary relationship between objects affords an action.

Object-scaled information and events

Complementarities between objects or parts of objects have been studied under the heading of event perception (Cutting, Proffitt, & Kozlowski, 1978; Johansson, 1973). Cutting (1981) points out that the perception of events contains two kinds of invariants; topographic ones, which refer to structural ratios between object or parts of objects in space, and dynamic invariants, that refer to invariant ratios in time. Both kinds of invariants are assumed to constrain each other. According to Michotte (1963/1991), action can be regarded as the production of an event in which the actor participates. The perceiving organism is involved, not merely as 'observer' but as 'maker' as well. In a tool use event, a tool user has the role of the 'motor' object.

The tool user is producing an event, of which the final state was the desired outcome in the beginning. In other words, there must be some form of intentionality: the whole event subserves reaching a certain state which terminates the event. This implies that at least the actor has to be able to envisage the event he is producing at some level as an integral whole. He has to perform an action on the intermediate, the tool, which in turn has to perform an action on the target object, caused by the users activity. Because in the end the tool's 'action' on the target realizes the goal of the actor, he has to able to see in advance the possibility of using the tool as a means to his end. In other words, to perceive the affordance of the tool implies to have a prospective view of the entire structure of the event that leads to the realization.

The obvious question, in how much detail is the actor able to foresee the event structure is closely related to the question what the units of the event structure are. Therefore, a further specification of our views will have to proceed through a discussion of this issue. According to Cutting (1981), a minimum principle (Leeuwenberg, 1971; Restle, 1979) could be applied to obtain an event structure with least number of components to adequately describe the event. Cutting envisaged object motion components. If the perceiver is actively participating in the event, however, such a view needs modification. Gibson points out that events can have affordances and that they could change the affordances of a situation. Actions could bring about these changes. Shotter (1983) describes action as "that aspect of human activity in which people make a difference in their environments" (p. 32). An unfolding action-event will lead to changes in the situation, leading to new affordances. This allows that the action could procede with minimal subjective control demands. A full specification for control purposes of the event structure in advance is not necessary, as the unfolding action leads to affordances which could take the role of controlling the action. We must look for the minimal units that are sufficently specific to allow these controls to evolve. What is sufficient depends on the actor's goal, his or her skills and the physical constraints of the situation. When the actor is less sensitive to the affordances resulting from the unfolding event, he must rely more on his internal controls. Accordingly, the units of the event can only be determined relationally, from the event context itself.

According to Gibson, (1979) events have a structure consisting of discontinuities in the stream of information. In the case of changes in the layout of surfaces, discontinuities concern, for example, changes in the topological relationships between objects (e.g. the realization of spatial contact). We may follow this approach in our definition of units of the event structure as intervals that are bounded by such discontinuities. For instance, if the goal is eating with a spoon, grasping the spoon in the manner appropriate for eating could be a unit in the overall act of eating. If so, its borders must be marked by discontinuities. The discontinuitity that marks the beginning is the initiation of the hand movement, the discontinuity marking the ending of the episode is the realization of contact between hand and spoon.

Which discontinuities are selected as boundaries, and which ones are considered irrelevant, may depend on the context. For eating with a spoon, a skilled spoon user should not differentiate the grasping further into subunits. For a child, learning to eat with a spoon, subunits concerning the constraints of e.g. place of grasping, kind of grasp, etc, could be relevant. Depending on an actors skill, the units are finer or coarser. Likewise, a different goal in the same situation (e.g. making noise with spoon and food) may lead to a description with different units for the action-event. Therefore, there is no user-independent complexity of the event structure.

The contex-sensitivity of both complexity doesn't always preclude a comparison between situations. E.g. in a situation where some of the complementarities relevant for an action are already realized, there is of course no prospective perception of these events needed. In such a situation, therefore the same goal could be reached by perceiving a less complex structure. This suggests, more generally, that *number* of discontinuities in motion that specify the tool's function as a mediatory could be used as a first measure of complexity. Each discontinuity corresponds to the realization of a complementary relationships between actor, tool and target, relevant for the tool to function. In the following we will refer to this factor as the *number* of complementary relationships to be realized. *Number* refers to structural invariants in space (in the sense of Cutting, 1981) that are realized by an actor.

The dynamical invariants, by contrast, should refer to the way these structural invariants are realized in time. For tool use this concerns the temporal integration of those discontinuities that specify the 'mediatory' character of the tool and the 'motor' character of the actor. In the following we will refer to this factor as the *kind* of temporal integration. Which discontinuities are relevant and how they are to be temporally integrated in the event structure depends on the situation on hand. The amount of skill, or knowledge required depends on the amount, and structure of physical, mechanical, constraints one has to meet during action.

As mentioned earlier in our introduction, an approach that uses merely *number* as complexity measure, will not be able to make predictions that are better than the ones from a cognitivist approach, e.g. because the complexity of subassembly strategy (Greenfield, 1991) could be modelled so as to covary with *number* complexity. By contrast, *kind* is specific to the ecological approach.

***Number* of complementary relationships** Consider an object out of reach which can be obtained with a hook. We assume the target out of reach to be within the crook part of a hook. Obtaining the target requires pulling the hook. In terms of our theoretical concept there are two first-order complementarities to be realized. One between hook and target (A_{end}) that corresponds to the goal of the action, i.e. the reachability of the target, and one between actor and hook (A_1) that correspond to the action to be performed on the tool in order to reach the goal. A complementary relationship between tool and target is already realized, so that for reaching the target, the actor merely has to pull the hook in a manner that the hook moves the target towards the actor. This event to be produced in the tool use action is characterized by the production of two discontinuities. The event structure is mirrored by the second-order affordance structure that refers to the integration of the two first-order complementarities A_{end} and A_1 (see Formula 1).

***Kind* of temporal integration.** The factor *kind* allowes to describe how in complex action different complementary relationships between actor and environment are to be realized in time. In a higher-order affordance structure, the relationship between mechanical characteristics as well as the skill level of the actor constrain, how these different complementarities are to be realized in time, in sequence (diachronously) or in parallel (synchronously). Because the target in our task can only be moved by the hook while the actor pulls it, A_{end} and A_1 must be realized at one moment, *synchronously*. (*Synchronous* integration is indicated in Formula 1 by a period separating A_{end} and A_1). There are cases, in which different complementary relationships can be realized one by one, in a temporal sequence. This kind of temporal integration is called *diachronous*. (Diachronous integration is indicated in the formulas by a comma separating lower-order complementarities).

If in the hook task, the target initially is not yet within the crook part of the hook, this position must be realized before the target can be moved by pulling the hook. The required complementary relationship between tool and target (O_0) must be ralized by an extra action on the tool (actor-tool). This action refers to a subevent consisting in analogy to Formula 1 of two discontinuities that refer to the integration of two complementary relationships A_0 and O_0 into a second-order affordance structure (see Formula 2). A_0 and O_0 are to be realized simultaneously. They are therefore described as *synchronously* integrated into the second-order affordance structure $A^2{}_2$. To describe the complete event structure for obtaining the target in this case, the two second-order affordance structures $A^2{}_1$ and $A^2{}_2$ have to be put in their appropriate temporal relation. They can be realized in sequence. Therefore the third-order affordance structure in Formula 3 (see p. 42) is a *diachronous* one.

1) $A^2{}_1(A_1.A_{end})$

2) $A^2{}_2\ (O_0.A_0)$

3) $A^3{}_1\ ((A_1.A_{end}),\ (O_0.A_0))$

The affordance structures in Formulas 1 and 3 differ with respect to *number* and *kind* of temporal integration. That such differences in complexity could influence the difficulty to perceive an object as tool is suggested by the results of Köhler 1917. A stick was perceived as a tool in a situation where it was in spatial contact with the target, but not if otherwise. Spatial contact could be viewed as a tool-target relationship already realized in the first situation, but merely possible in the second. Thus the difficulty of perceiving the tool function of an object depends on the complexity of the event structure to be perceived, in order to produce the action. Complexity was measured by *number* and *kind* of temporal integration. The factor of *number* will be investigated in Experiments 1 and 2. It will be argued that the factor kind is also needed to explain all data. In Experiment 3 we shall deal with the factor *kind*.

Experiment 1

Introduction

Experiment 1 was performed to obtain an initial evaluation of our description. The task was to bring a target within reach with the aid of a hook. The spatial relationship between hook and target was varied. Therefore, in order to perceive the hook as a tool in the configurations, event structures of different complexity must be anticipated. Children of different ages were compared with respect to their ability to perceive the hook as a tool in the five configurations of Figure 2. We sought to determine an age group sensitive to the difficulty of our conditions. If a child can use tools in some, but not all of the configurations, he will be able to do so in those which possess a less complex affordance structure.

Choice of the configurations. For all the configurations in Figure 2, the hook functions only if the crook is oriented towards the target, hook and target are in contact and the target lies within the crook. As will become clear, the event structure that leads to this end is similar for all configurations. The highest-order affordance structure requires *diachronous* integration, whereas all nested ones are *synchronous*. This allows the comparison of the affordance structures with respect to the *number* of second-order affordances at third-order level to be meaningful. The fewer relations in Figure 2 are realized, the more second-order *synchronous* affordance structures are contained in the third-order affordance structure. Therefore, the more difficult it will be to perceive the tool function of the hook.

Diachronous affordance structures impose weakest possible integration demands. There may be more sophisticated ways of actually performing the task. We do not exclude that the nested second-order affordance structures are realized *synchronously*. This, however, does not affect the *number* of affordances to be integrated.

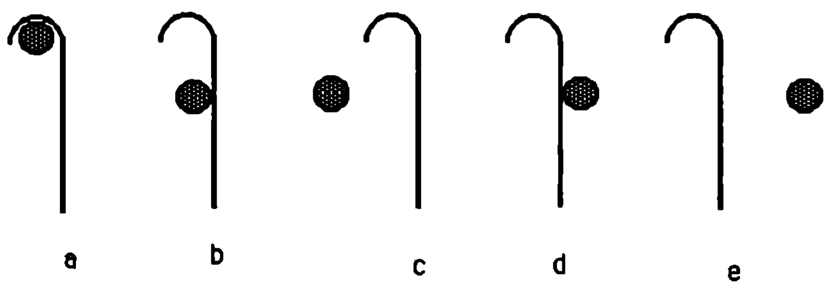

Figure 2: Configurations from Experiments 1-2

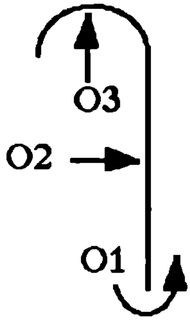

Figure 3: complementary relationships between tool and target that should maximally be changed in the given configurations for using the hook as tool.

Affordance structures of the configurations. The three relationships between tool and target that matter in Figure 2 are the crook orientation of the hook with respect to the target, the spatial contact between the two and the height of the target with respect to the hook. In Figure 3 these are indicated as O_1, O_2 and O_3 respectively. If one of these is already realized in a configuration, there is accordingly one discontinuity less in the event structure. The actor shouldn't even be aware of the realization in the same sense as a driver doesn't need to know how the engine of his car is constructed in order to drive, as long as it works.

Table 1 contains the first-order complementarities involving the actor-tool and actor-target relationships, as well as the ones between tool and target specified in Figure 3. A_1-A_3 correspond to the actions to be performed in order to realize O_1-O_3. The affordance A_{end} is the reachability of the target, i.e. the end to which the hook is the means. A_{end} can only be realized by means of A_4, that indicates the pullability of the hook. Realizing A_4 leads only to A_{end}, however, if the target is within the crook. Thus temporal integration of those first-order complementarities into a second-order affordance structure is required. The second-order affordances are given in the last column of Table 1. Besides the one that relates A_4 to A_{end}, there are three more second-order affordance structures for relating $A_{1\text{-}3}$ to $O_{1\text{-}3}$ respectively. The third-order affordance structures that specify the tool function, integrates different numbers of these second-order affordance structures for Configurations a-e. How many are needed for each is shown in Table 2.

In Configuration a, all required tool-target complementarities from Figure 3 are already realized. As just pulling the hook in Configuration a realizes the tool function no third-order level integration is required. For the others there are third-order affordance structures of increasing complexity. Configuration d has an equally complex higher-order affordance structure as Configuration e. This, although spatial contact exists between hook and target in Configuration d. However, spatial contact is not functional for hook use before the proper orientation is realized. Spatial contact (O_2) thus is subordinated temporally to the proper orientation (O_1). Since in Configuration d the proper orientation (O_1) is not yet realized, *functional* contact (O_2) has to be anticipated like in Configuration e. *Number* of second-order affordance structures for all configurations is specified in the last column of Table 2.

Table 1: first-order and second-order complementarities of the hook.

actor-hook	**hook-target**	**actor-target**	A^2
A_1	O_1 orientation		$(A_1.O_1)$
A_2	O_2 contact		$(A_2.O_2)$
A_3	O_3 height		$(A_3.O_3)$
A_4		A_{end}	$(A_4.A_{end})$

Table 2: *Number* complexity of five tool use configurations.

Configuration	hook affordance structures	number
a	$A_a^2\ (A_4.A_{end})$	1
b	$A_b^3\ ((A_3.O_3), (A_4.A_{end}))$	2
c	$A_c^3\ ((A_2.O_2),(A_3.O_3), (A_4.A_{end}))$	3
d	$A_d^3\ ((A_1.O_1),(A_2.O_2),(A_3.O_3), (A_4.A_{end}))$	4
e	$A_d^3\ ((A_1.O_1),(A_2.O_2),(A_3.O_3), (A_4.A_{end}))$	4

Note. number regards the second-order affordance structures to be integrated temporally for Configurations a-e.

Hypotheses. The prediction according to Table 2 is called the *number* hypothesis of Experiment 1. This hypothesis predicts relative difficulty of the configurations, according to the complexity of the tool affordance structure: $a < b < c < d = e$.
An alternative hypothesis could be obtained from a research tradition directly inspired by Köhler (1917). Köhler had noticed that the lack of spatial contact between a stick and a target made it difficult to perceive the stick as tool. Accordingly, Zhukova (1960) concluded that the relevant configurational property is whether tool and target together could be viewed as one object. Tool and target would be viewed as one object if they are in spatial contact, based on the law of proximity. Köhler himself never formulated such a hypothesis, but through the follow-up research of Bates et al. (1980), this hypothesis became known as the explanation from Köhler's Gestalt psychology. We will therefore compare our predictions with ones from this *contact* hypothesis. Since there is spatial contact between target and object in Configurations a, b and d, these are predicted by the contact hypothesis to be less difficult than Configurations c and e. In addition, no differences are predicted between a, b and d and neither between c and e.
In our view spatial contact between tool and target is not important as a cue for object identity. Spatial contact may facilitate the anticipation of the goal state, as in Configurations a and b and therefore we agree with the contact hypothesis in predicting that these configurations will be easy. But both approaches diverge in their prediction for Configuration d, in which the spatial contact is not functional. According to the contact hypothesis, the difficulty of the configurations will be: $a \sim b \sim d < c \sim e$

Method

Subjects. The experiment was performed in eight nursery schools in the Dutch towns of Breda and Nijmegen. Parents and nurses had been contacted by letter explaining the purposes of the experiment and asking permission for the the children's participation in our experiment. Fiftyseven infants and young children between 8 months and 3.4 years of age, 26 females and 31 males participated in the experiment. The subjects were divided in two different treatment groups according to age, the "younger" ones (between 8 and 22 months) and the "older" ones (between 23 months and 3.8 years).

Stimuli. The five configurations shown in Figure 2 were used.

Material. Plastic hooks, about 60 cm long, approximately 12 mm cross-section, 12 cm width at the crook part and with a weight of 75 g (sufficiently light for the child to handle), were used. It is important that children have motoric skills sufficient to perform elementary actions with the hook. Their ability to handle, lift, aim and transport were observed in a familiarization phase. The experiment was performed at a 1.20 x 2 m table adjusted to normal children's location. As targets, cookies of 10 cm in diameter were used during the training and in the first experimental trial. In subsequent experimental trials, we used checkers for the "older" treatment group and 6 different little rubber animals of about 10 cm in diameter and height for the "younger" group. These differences, as well as some differences in procedure, were considered essential to motivate both groups equally for the task. The "younger" group was given a likeable toy as target and the "older" group a checker, because for the latter group, the experiment was intrinsically motivating as a game. Securing motivation was believed to be more important than dragging them through outwardly identical procedures, disregarding motivation. We are aware that as a consequence, differences between the "older" and "younger" groups may be ascribed to these differences in treatment. If, however, the trends within the groups are consistent with the trend between the groups, we have a check on the validity of our disregarding these differences in treatment. During the experiment, older children stood in front of the table on a 30 x 30 x 5 cm concrete flag-stone which marked the middle position. An assistant experimenter (a teacher or mother) was behind the child. The younger children were sitting on the assistant experimenter's lap. This was done in order to assure that children in the younger as well as in the older group were in contact with the table, their hips about 10 centimeter below the top of the table. In this way the action radius for both groups was made comparable. The whole set-up is shown in Figure 4.

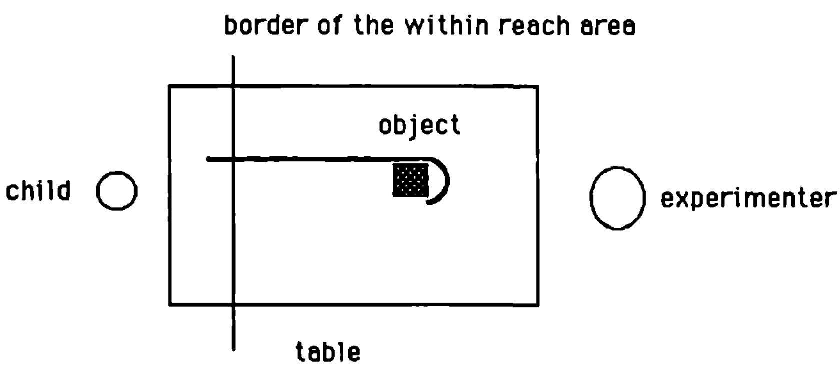

Figure 4: Experimental setting used in Experiment 1

Procedure. The experiment consisted of three phases, of which Phases 1 and 2 were for instruction and Phase 3 was the experimental phase. Phases 1 and 3 were identical for the "older" and the "younger" groups, whereas Phase 2, the second part of the instruction, differed. In Phase 1, children were given the opportunity to become familiar with the hook. A child received the hook for approximately two minutes of free manipulation. Then the experimenter took the hook back. Phase 2 was performed in order to make clear what is within reach. On entering Phase 2, a toy was presented out of reach to the "younger" group. Children showed interest in the toy by trying to approach it by all possible means, e.g. reaching for it, climbing on the table, etc. Climbing, however, was prevented by the assistant experimenter during this phase and the next ones. In this manner, the child is familiarized with the impossibility in these configurations to obtain the target desired by such direct means as reaching or climbing. Such restrictions on exploration the child is familiar with from everyday experience. They are therefore ecologically valid. If the child showed no interest in the toy, another one was tried. Children who showed no interest in any of the toys were dismissed from further participation.

In the "older" group in Phase 2, a child was shown a checker three times subsequently, the first time within reach, the second time at the border of the within reach area and the third time out of reach. Each time the child was asked if he or she could get the checker. If it was clear to the child that the first two checkers were within reach but the third one was not, a cookie was placed out of reach for the child and the experimenter asked if the child wanted to have the cookie. If the answer is "yes" the child is admitted to Phase 3.

Phase 3, the experimental phase, was the same for both treatment groups. Configuration a (the easiest one according to both alternative hypotheses) was always presented first. In subsequent trials, the Configurations b-e were presented in random order. In order to control the motivation in the "younger" group, the target was brought within reach after each trial. If the child started playing with it, the child was assumed to be still motivated and the experiment continued. If not, the child was dismissed from the experiment. The orientation of the hook (left or right) was balanced between subjects. Before a configuration was presented, the assistant experimenter covered the table from the child's view with a huge picture book. She pointed out pictures in the book for the purpose of distracting the child from the experimenter. Meanwhile, the experimenter positioned a tool use configuration on the table. Then the book was removed so the child could see the configuration. The experimenter asked: "Can you make this cookie (or the animal) come to you" (The phrase: "Can you get the cookie" would not work well in Dutch, because of the grasping connotations for almost all

Dutch equivalents of 'getting'). A video-camera registered the behaviour of the child. If he or she attempted to climb on the table, this was prevented by the assistant experimenter. If, after some time there was no successful tool use, the child was given a small hint: the assistant experimenter pulled the hook approximately 5 cm in the direction of the child and the child was allowed to try again. If the small hint still didn't lead to success, the assistant experimenter fully modelled the required action with the hook, put it back in its original position and allowed the child to try it once more. Models were given in order to exclude any kind of socially motivated prevention of a solution or a lack of concentration, for instance as a result of being totally fixated on the target. Subsequently, regardless of whether the child had been unsuccessful or successful directly, after a hint or after a full model, the same configuration was presented once more. This repetition of a trial was performed in order to make sure that an eventual success or failure was not a coincidence. Ultimately successful solutions with or without a model were counted separately. Children who didn't get a cookie after the first trial were given one.

Results and Discussion.

Because both the *number* hypothesis and the contact hypothesis apply only to those children who are able to solve some but not all of the configurations, our analysis must begin by distinguishing them.

Three groups were distinguished: the unsuccessful group that solved the tool problem in less than 33% of all configurations given (n = 14; mean age = 10.6 months; sd = 1.83). The half-way group with children who had success from 33% up to 66% of the configurations (n = 29; mean age = 20.1 months; sd = 3.64). Finally, the successful group with children who had success in more than 66% of the configurations (n = 21; mean age = 30.1 months; sd = 5.02). The half-way group is a mixture of the "older" and "younger" treatment group. Within this half-way group, performance of subjects from the "older" and "younger" treatment group is similar. This suggests that we may neglect the differences in procedure between these groups due to our decision to control motivation. The unsuccessful group consists only of children from the "younger" group and the successful group has only "older" ones. It was assumed that the predictions of both the *number* hypothesis and the contact hypothesis primarily apply to the half-way group. From the other groups, the unsuccessful ones are assumed to be unable yet to perceive the function of the tool, whereas the successful group may fail to discriminate, because their large percentages of success provide a ceiling effect.

(for the observation categories, see Appendix 1).

For all three groups, the percentages of success are shown in Figure 5 for the Configurations a-e. Success in a certain configuration is defined as obtaining the target independently by means of the tool for two times, regardless of having a model or not. An analysis of variance concerning the mean success over all configuration yields a main effect for the three groups ($F_{2,8} = 51.148$, $p < 0.001$).

The following results are of the half-way group. Within group differences concerning the frequency of success per configuration were tested with McNemar chi-square procedure (for the significances see Appendix 2). From the comparisons we get the following relations:

Difficulty of Configuration	$a \sim b < c < d < e$
number hypothesis	$a < b < c < d \sim e$
contact-hypothesis	$a \sim b \sim d < c \sim e$

Significant differences between Configurations b and d as well as between Configurations c and e are evidence against the contact hypothesis.
The *number* hypothesis is more in accordance with the experimental results. However, two of the ten possible relationships are not in accordance with the predictions, viz. the expected difference between Configurations a and b failed to occur. Instead, there was an unexpected difference between Configurations d and e. Both deviations are in favour of the contact hypothesis. So we need to further analyze the data in order to decide about the role of spatial contact.
From Figure 5, it is likely that the nonsignificance of the difference between Configurations a and b is due to a ceiling effect. The unexpected difference in Configurations d and e, however, suggest that a refinement of our assumptions is necessary. Our theoretical description was based on the assumption that the child could only bring the target within reach by placing the crook of the hook behind it and pulling. Our materials afford another possibility not yet taken into account. This possibility would be to use the hook as a stick, pushing the target in a circular movement within reach. This stick use according to the affordance structure concept necessarily requires a different affordance structure than hook use because different relationships are implied between actor, tool and target. Therefore this result doesn't necessarily speak against the assumptions of our approach, provided that the affordance structures of stick use could be taken into account.
In order to find out if stick use may be responsible for the difference between Configurations d and e, we searched the data of successful children for stick use. In Configuration a to c the hook was used as a stick for 15% of the solutions but in Configuration d and e this occurred in 50% of the cases.
For both tools, hook and stick, there are two higher-order complementarities to be realized. One concerning the reachability of the target by decreasing the distance between actor and target and as a condition for doing so the maintenance of spatial contact between tool and target. In the case of hook use, maintaining contact between hook and target in the crook part of the hook is realized by the shape of the crook part itself. Once the proper position of the target within the crook part of the hook is realized, then subsequently, the actor has to decrease the distance of a crook to himself by pulling a handle. Contrary for stick use. Here, maintaining the contact between stick and target and decreasing the distance between actor and target must be realized *synchronously*. Whereas decreasing distance of the target to the actor refers to a principally vertical movement, maintaining the contact requires a horizontal movement. The shape of a stick requires that the two must be realized at the same moment, resulting automatically into the sweeping movement characteristic of bringing the target within reach by a stick. These differences in temporal integration of lower-order

complementary relationships into higher-order affordance structures we called *kind* of temporal integration. It will be explored as a second source of complexity for the perception of the means character of a tool in Experiment 3.

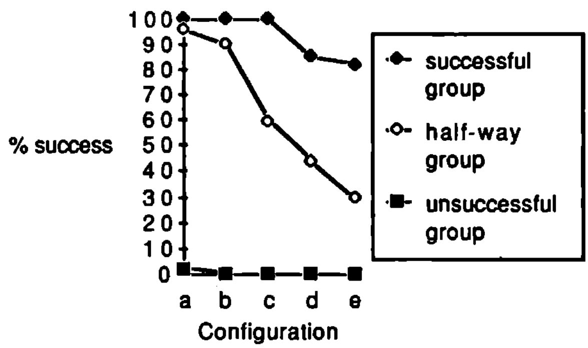

Figure 5: Results of Experiment 1. Percentages of children who succeeded in Configurations a-e for the three groups (unsuccessful group, half way group and successful group)

Our experimental procedure used a model to provide the child a demonstration of tool use in each configuration after initial failure to succeed. The significance of differences between the before and after a model was tested with Cochran's Q-Test (see Appendix 3). For the unsuccessful group, the low percentage success does not increase. This group seems to be not ready to make use of the model information. For the successful group, most subjects succeed without model. For the half way group, there is a significant increase of success after a model for Configurations that are easy according to our theoretical description (Configurations a-c), but not for the more difficult ones (Configurations d-e).

The role of modeling could be understood as a clarification of the information available from the configuration given (see Vygotsky, 1986). The complementary relationships a child has to anticipate in order to solve the respective tool use problem are realized in front of the child. We thus assume that the child is doing more than just imitating an action. The model helps to bring the relevant complementary relationships into focus. The child must be ready for this, in order to profit from the model.

A prediction resulting from this assumption may distinguish the behavior of the child following the model from pure imitation behavior. Because a more complex configuration contains all affordances also involved in the easier configurations but not vice versa, a child successful in a certain configuration, with or without a model, is able to anticipate all relevant complementary relationships. This implies that he or she will succeed in all the theoretically easier configurations.

Experiment 2

Hypothesis and method

If success after a model requires the same capabilities of the perceptual system as success without model, both must imply the solution of all theoretically easier configurations. In order to test this prediction Experiment 2 was performed as a replication of Experiment 1 with a modified procedure: Instead of a random order of the configurations, a fixed order is used starting at the first trial with one of the theoretically most difficult configurations (Configurations e and d in Figure 2), followed by the others in decreasing order of difficulty (c, b, a). If the temporal integration demands determine the difficulty of Configurations a-e, then any child succeeding in a particular configuration (if necessary, after modeling) will also succeed in all following configurations without a model, because the model has helped the child to figure out the potential complementarities of a configuration, that are more complicated than those in all following ones. A model was given if the child after some time did not succeed. As in Experiment 1 first a small hint was given and if this didn't help, the solution was fully demonstrated by the person on who's lap the child was sitting. After a model the same configuration was presented ones more.

Subjects This experiment took place in two nursery schools in the town of Nijmegen. Twelve children between 1.8 and 2.1 years old, 6 girls and 6 boys participated in the experiment. Parents and teachers had been contacted by an explanatory letter and had been asked for their permission.

Results and Discussion

In Table 3, successes and failures for all five Configurations a-e are shown for the 12 children participating in this experiment. As predicted by our hypothesis, children succeeding after modeling in a particular configuration succeed without model in all the following configurations. There is not a single violation of this prediction in 60 trials. We may conclude that children's success with or without model means the ability to anticipate the temporal integrated relationships of actor, tool and target, necessary for solving the respective task, not just imitating the behavior of the model.

Table 3: Results of Experiment 2.

Config.	Subject											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
a	+	+	+	+	+	+	+	+	+	+	+	+
b	+	+	+	+	+	+	+	+	+	+	+	+
c	+	+	+	+	+	+	+	+	+	m	-	-
d	+	+	+	+	+	m	m	-	-	-	-	-
e	+	+	+	m	m	-	-	-	-	-	-	-

Note. Conf. = configuration; Successful solutions are indicated by "+", failure by "-"; successful solutions only after a model are indicated by "m".

Summing up the results from the first two experiments, we found a group (called the half way group according to the results in Experiment 1) of children sensitive to our variations in task complexity. This group has an age range from 14 months to 25 months. They solved up to 66% of the configurations given. There was no subject who succeeded in a configuration theoretically described as more complex and failed in a configuration theoretically described as less complex. At least for the half way group *number* of affordances to be integrated temporally is a source of difficulty for perceiving the tool function of a hook in our experiments.

Experiment 3

Introduction and hypothesis

It was assumed that besides according to *number*, affordance structures could also vary according to *kind* of temporal integration. In a sense, *kind* is a complexity criterion much more specific to our theoretical approach than number. *Kind* involves the temporal characteristics of the integration and is therefore more distinctive a characteristic of the event structure of action.

Von Hofsten & Rönnqvist (1988) showed how the temporal integration of effectivities like reaching and grasping develop in infants between 3 and 9 months. For 3-month-old infants the reaching and grasping affordances were realized in a fixed order, one by one in a *diachronous* way. With the 9-month-old, they are realized in parallel in a smoothly integrated action. We could view this as a realization of a *synchronously* integrated affordance structure.

Whereas the grasping could be realized by *diachronous* as well as by *synchronous* integration, there are cases where *synchronous* integration is necessary. For instance driving a car requires sometimes changing the gear and turning the driving wheel at the same moment.

According to our theory, *synchronous* integration is more complex than a *diachronous* one, not only for action, but also for perception. In the case of *diachronous* integration the relevant complementary relationships are separated in time by discontinuities of the event structure. The realization of one of these is the signal for the next one to begin. In the case of *synchronous* integration, however, one discontinuity in the event structure specifies more than one complementary relationship to be realized. The phenomenal event structure of an action whose possibility must be perceived is likewise subject to more specific constraints. So, as far as perception of tool affordance structures is concerned, the overall *kind* of temporal integration of lower-order affordances into a higher-order one may be used to predict for task difficulty.

Experiment 3 was performed in order to pit *kind* of temporal integration against *number*. Two alternative solutions were contrasted for one task. The possibility of two alternative solutions was already observed for the configurations of Experiment 1. They could, in principle, be solved by hook or by stick use. An unexpected difference occurred in Experiment 1 between Configuration d and e was ascribed to stick affordance structures. Hook and stick affordance structures differ primarily in the *kind* of integration, hook affordance structures being *diachronous* and stick ones *synchronous*. Two second-order affordance structures must integrated *synchronously*, to perceive the possibility of the characteristic sweeping movement that brings the target within reach by a stick. One is the possibility of decreasing the distance between target and actor by a centripetal movement of the target. The other one is the ability to maintain the point of contact between stick and target, by means of a lateral movement.

As compared to *kind*, which is a property of an affordance structure, *number* is a property of its arguments and it is, therefore, a complexity of a hierarchically lower level. One might therefore expect kind-complexity to dominate over number-complexity. In that case one would interpret the analytical hierarchy of the affordance structure as a hierarchical control structure with top-down control. Alternatively, bottom-up control would lead to the prediction that number-complexity dominates kind.

A third possibility is that there may be trade-off between *number* and *kind* of affordance structure. If so, we may expect the lower level *number* complexity sometimes to overrule the advantage of *diachronous* over *synchronous* dichotomy at higher level. Thus, a change in preference from hook use to stick use can be expected if stick use is much cheaper with respect to *number* complexity than hook use.

Trade-off assumed between the two sources of complexity leads to the prediction of a critical point where preference for a more *diachronous* affordance structure with a relatively long sequence of affordances converts to a preference for a more *synchronous* affordance structure with less affordances to be integrated. We have at present no theoretical criterion for the position of this point. In the present experiment we will therefore determine this point empirically.

Choice of configurations

As our starting point, we took the configurations of Experiment 1, where stick solutions occurred to some extent. These are the Configurations b and d of Figure 2. Observation data on Experiment 1 revealed that for Configuration b the number of stick solutions was less than 10 % of the total whereas for Configuration d the number of stick solutions was more than 50 % of the total. We constructed variations of these configurations for our purpose.

These, shown in Figure 6 had maximal variation on *number* for the hook affordance structures, but minimal for the stick ones. Hook and stick affordance structure in Configurations a, b and c have nearly equal *number* complexity, but differ in *kind*. For this configuration preference for hook use is predicted. For configurations d, e and f the *diachronous kind* solution, the hook is extremely disadvantageous with respect to *number*. For this configuration, stick use is predicted if there is trade-off between the levels.

Description of the affordance structures. Figure 7 shows the complementary relations for hook (a) and stick (b). For hook use these are the inclination of the hook-target pair with respect to the actor (O0), the orientation of the crook part of the hook with respect to the target (O1); the contact between hook and target (O2); and the height of the hook with respect to the target (O3). For stick use the tool-target complementarities are the position of the stick above the target and the spatial contact between the two.

For hook and stick use A_{end} indicates the complementary relationship that correspond to the goal of the action, i.e. the reachability of the target. A_4 and A_3 respectivelly indicate the tool-target complementarity to be realized in order to realize A_{end}. Tables 4 and 5 contain the tool-target complementarities (O) and actor-tool ones, or first-order complementarities (A) that are needed. The temporal integration of these first-order complementarities into second-order affordance structures (A^2) are shown in the last column. Finally, Table 6 contains the temporal integration of these into third-order affordance structures (A^3) needed. *Diachronous* integration is indicated by a comma separating the lower-order complementarities and *synchronous* integration by a period. Table 7 summarizes the *number* complexity for both hook and stick use. Number has been split up into *synchronously* and *diachronously* integrated ones. The zeros in the column labelled "synchronous" for hook use indicate that all the hook affordance structures are of the *diachronous kind.* Configuration a, for instance, affords a sequence of actions: first, bringing the target within the crook part of the hook. Then pulling the hook towards the actor in order to bring the target within reach. The point of contact between hook and target is maintained because of the hook shape. All these affordance structures occur also in the *diachronous* structure of Configuration b, where in addition the right orientation of the crook part with respect to the target must be realized. In Configurations b and c as well as e and f the crook must be given a vertical inclinatio first with respect to the actor.

In Table 7, the zeros for most of the *diachronous* stick affordance structures, show that the stick affordance structures are of the *synchronous kind.* Configurations e and f in Figure 6 differ only slightly from the complete synchronicity in the others, as their *number* complexity shows. Our description is based on lifting the stick and bringing it to the other side of the object, followed by a short "sweep". A completely *synchronous* affordance structure was possible for these configurations as well. Because of the actor's location the sweep than must have a wider turn than for the other configurations.

The last column of Table 7 shows the difference in *number* between stick and hook use. It is low for Configurations a-c and high for Configurations d-e. The switch from hook to stick use is therefore expected to occur between Configurations c and e. Whether the predicted switch is going to occur exactly here cannot be predicted from our theoretical description. In the trade-off view this depends on the relative strength between *kind* and *number* in the transaction, which is unknown.

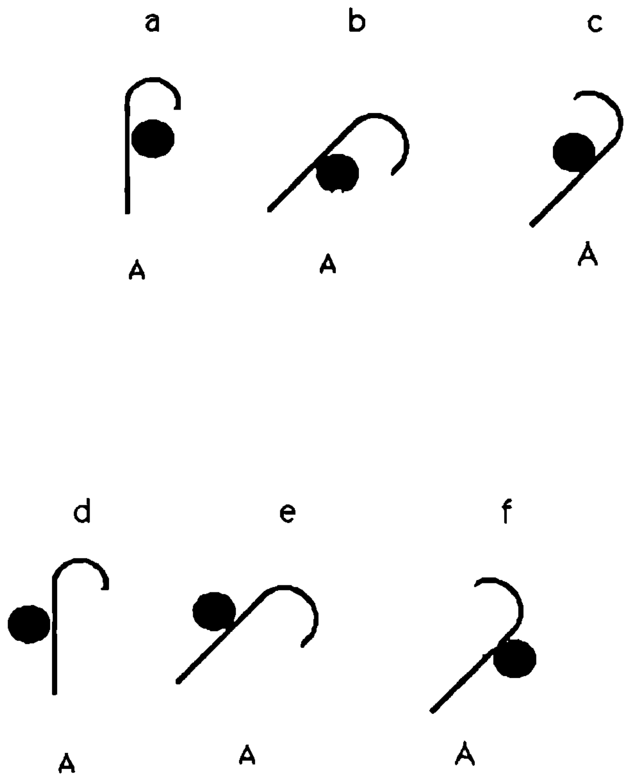

Figure 6: Configurations from Experiment 3.

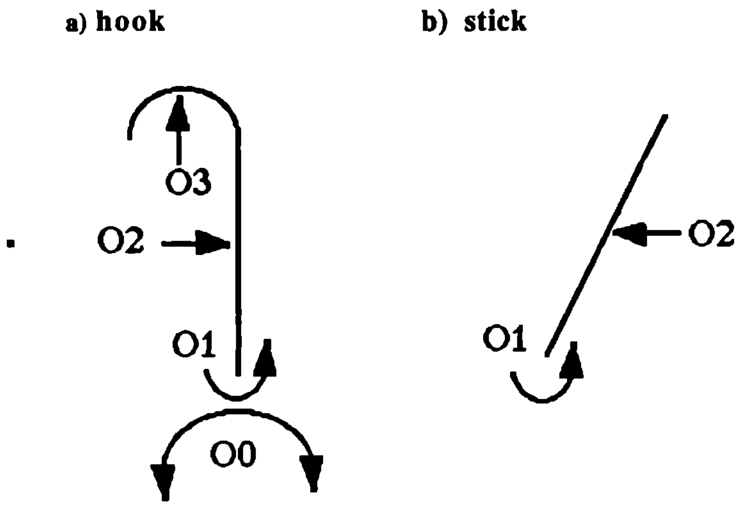

Figure 7: Possible or actual complementary relationships between tool and target in Configurations a-f for hook use (a) and for stick use (b).

Table 4: First and second-order complementarities for the hook. Further explanations see text.

actor-hook	hook-target	actor-target	A^2
A_0	O_0 - inclination		$(A_0.O_0)$
A_1	O_1- orientation		$(A_1.O_1)$
A_2	O_2 - contact		$(A_2.O_2)$
A_3	O_3 - height		$(A_3.O_3)$
A_4		A_{end}	$(A_4.A_{end})$

Table 5: First and second-order complementarities for the stick. Further explanations see text.

actor-stick	stick-target	actor-target	A^2
A_1	O_1- position		$(A_1.O_1)$
A_2	O_2- contact		$(A_2.O_2)$
A_3		A_{end}	$(A_3.A_{end})$

Table 6: Affordance structures for Configurations a-f according to hook and stick use.

Hook affordance structure	Stick affordance structure
A_a^3 $((A_3.O_3), (A_4.A_{end}))$	A_a^3 $((A_2.O_2). (A_3.A_{end}))$
A_b^3 $((A_0.O_0), (A_3.O_3), (A_4.A_{end}))$	A_b^3 $((A_2.O_2). (A_3.A_{end}))$
A_c^3 $((A_0.O_0), (A_3.O_3), (A_4.A_{end}))$	A_c^3 $((A_1.O_1), (A_2.O_2). (A_3.A_{end}))$
A_d^3 $((A_1.O_1), (A_2.O_2), (A_3.O_3), (A_4.A_{end}))$	A_d^3 $((A_2.O_2). (A_3.A_{end}))$
A_e^3 $((A_0.O_0), (A_1.O_1), (A_2.O_2), (A_3.O_3), (A_4.A_{end}))$	A_e^3 $((A_1.O_1), (A_2.O_2). (A_3.A_{end}))$
A_f^3 $((A_0.O_0), (A_1.O_1), (A_2.O_2), (A_3.O_3), (A_4.A_{end}))$	A_f^3 $((A_2.O_2). (A_3.A_{end}))$

Note. *Diachronous* integration is indicated by a "," to separate lower-order affordances and *synchronous* integration by a ".".

Table 7: *Number* complexity split out for *diachronous* and *synchronous* affordance structures.

Configuration	hook use		stick use		difference
	diachronous	synchronous	diachronous	synchronous	
a	2	0	0	2	0
b	3	0	0	2	1
c	3	0	1	2	0
d	4	0	0	2	2
e	5	0	1	2	2
f	5	0	0	2	3

Note. "difference" = (Column 2+ Column 3) - (Column 4 +Column 5)

Method.

Subjects. This experiment was performed in four day-care centers in the Dutch towns of Nijmegen and Wychen. Parents and teachers had been contacted by letter, explaining the purposes of the experiment and asking for permission for the child's participation. Thirty-five young children between 17 and 48 months old participated in the experiment.

Stimuli. Twelve configurations were used, the six configurations shown in Figure 6 and their mirror image variations, in which left-hand side and right-hand side were exchanged.

Material. The same plastic hooks as in Experiment 1 were used. The experimental toys were six small, plastic, 'squeaky' animals, about 10 cm in height and 6 cm in diameter (two differently coloured rabbits, two differently coloured doggies, a frog and a lion). In the training phase, two nonexperimental toys were used (a stuffed cloth dog or a rabbit). The experiment was performed at a table of normal children's height. On this table a perspex plate was placed with a grid engraved into the bottom, so that the

movements of hook and objects could be studied better in the video-recordings.The grid was hardly visible for the child.
During the experimental session, the child was seated on the assistant experimenter's lap (a teacher or occasionally the mother). This was done in order to supply the child with a safe 'operating base' from where it might be less anxious to perform, as well as preventing the child from reaching too far across the table and obtain the object by reaching.

Procedure. The experiment consisted of two phases. During Phase 1, the child was familiarized with the experimental setup. After the child had been seated, a nonexperimental toy was placed out of reach for the child. The child's attention was drawn towards this toy by the experimenter by saying: "Look what a nice rabbit (doggie). Would you like to play with it? Can you make the rabbit come to you?" The child in general showed interest in the toy by reaching for it, or by trying to climb on the table (which was prevented by the mother or nurse). The experimenter concluded: "The rabbit can't come towards you, can it?" Then, the toy is tied to a string which is within reach for the child. The child's attention was once more drawn towards the toy by pointing and saying: "Now can you make the rabbit come to you?" If the child showed no initiative, the mother or nurse pulled the string a little so that the toy started moving. If the child didn't react at all or became afraid (which happened once or twice) a cookie was given and the session was stopped. If the child pulled the tool and succeeded to obtain the toy, Phase 2 followed.
Phase 2 was the experimental phase. The experimenter presented one of the six configurations on the table in front of the child. For each of the configurations, a different toy was used. She said: " Look what a nice rabbit (doggie, lion, frog). Can you make it come to you?" If the child dropped the tool, or the object fell off the table, or if it became otherwise impossible for the child to acquire the object with the tool, the configuration was presented a second time. If on two successive occasions the child did not succeed in acquiring the object with the tool, the pre experimental configuration was presented again. This was done to supply the child with a success experience to prevent that failure in the preceding configuration would distract the child from trying the next configuration. Every time Configuration a was presented, it was solved so it fulfilled the aim of providing the child a success experience.
After the toy was obtained (either in experimental trial or in Configuration a), the child was allowed some playing time. Before the next presentation the child was asked to give back the toy to the mother/nurse or the experimenter and it was put aside on the table "... so it can look and see what you are doing". If at any time during the session the child lost interest in the procedure, the toy was replaced by a cookie. This appeared

to be sufficient for the child to regain its attention and complete the session. More than one cookie was never needed. In this manner, six configurations were presented successively to each child. The order of the configurations was a prearranged random one, with left-right orientation for the hook alternating, and balancing the number of presentations of a left or right version of a configuration. After the child completed the six experimental configurations, he or she was given a cookie and a balloon in reward.

Scoring. Only the results of the first presentation of each configuration were scored. We did this in order to be sure that the child's action depended on the configuration presented and not on subsequent changes providing additional information. Apart from the behavioral aspects such as reaching, rotating, pulling, throwing etc. we registered whether the child was able to effectively acquire the toy using the tool (success-failure), and whether the tool was used as a hook or a stick. We only scored an event as hook-use if the crook of the tool was explicitly used as the part with which the toy was controlled and moved. That is, if the child explicitly and intentionally placed the crook of the tool around the toy. All other use was scored as stick-use.

Results and Discussion

Comparison between hook and stick use. The trade-off hypothesis predicted a shift in preferred usage from hook to stick. In order to test this hypothesis, frequency differences between hook and stick use were tested with the chi-square procedure for the comparison of two dependent samples (see Table 8). As shown in Figure 8, there is a preference for hook use in Configurations a-c and a preference for stick use in Configuration f. These results are in accordance with the hypothesis of trade-off between *number* and *kind*. They could not have been explained from either *number* or *kind* alone.

Provided that the affordances to be integrated do not differ in *number*, a *diachronous kind* of temporal integration is preferred that leads to hook use in Configurations a-c. Hook and stick use are equally preferred in Configurations d and e. For these, the difference in *number* between hook and stick use equals three.

In sum, as soon as the difference in *number* increases above two, the advantage of the lesser *number* outweights the disadvantage of the *synchronous kind* of integration and preference turns to stick solutions. This suggests that the trade-off uses as principle, to shift strategy if the task complexity is raised by two.

The preferences observed, however, could only indicate trade-off between *number* and *kind* if the shift in preference is actually observed within subjects. If our sample would consist of two groups only, one always preferring stick use and the other hook use, the result would be an artefact. The reason for choosing hook or stick then would be independent of the relationship between the affordance structures. We were able to distinguish, however, three groups of subjects (see Figure 9). The largest group switches between hook and stick use (n = 18), the second group uses the hook only (n = 13) and the third group uses the stick only (n = 4). Figure 9 suggests that the trade-off observed in Figure 8 between hook and stick solutions is entirely due to the switching group. This, because the frequencies no longer show an interaction when the scores of the switching group are removed from the data.

Probably the non-switching subjects were fixated to their first solution. They might have been looking for a similar one in all following configurations. These subjects are in a way "blind" for other solutions. This is the kind of behavior described by Duncker (1945) as functional fixation. An interesting result is, therefore, that for the two non-switching groups the percentage success (64.4 %) is smaller than for the switching group (76.8%).

Table 8: Results of Experiment 3: Differences in frequency of hook vs. stick use tested with the chi-square.

Configuration	chi-square	p
a	72.2	s.
b	4.4	s.
c	4.4	s.
d	1.3	n.s.
e	0.1	n.s.
f	5.4	s.

Note. Significances were tested with the chi-square test; s = significant; n.s. = not significant; p for chi-square 3.84, df = 1, alpha = .05, one-tailed test; n = 35

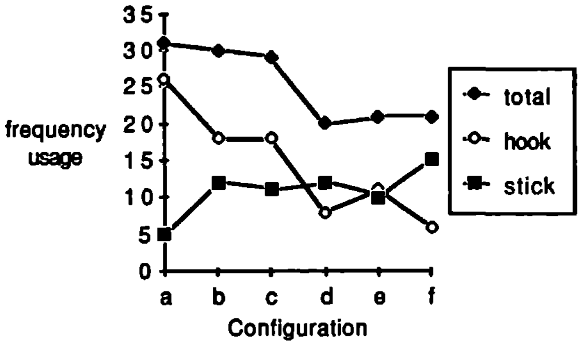

Figure 8: Absolute frequency of the total usage, stick use and hook use for all subjects (n = 35) in Configurations a-f of Experiment 3

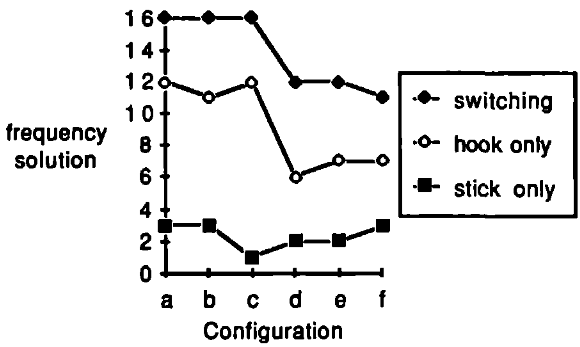

Figure 9: Absolute frequency of solutions for the group switching between hook and stick use (n = 18), the group using the hook only (n = 13) and the group using the hook as stick only (n = 4) in Configurations a-f of Experiment 3

Comparison within hook and stick solutions. Within-group differences for hook and stick use respectively in Configurations a-e were tested with the Mc-Nemar chi-square procedure (see Table 9 a, b). The within-group differences for both, hook and stick use are not predictable from *number* only. Only for Configurations a, b and c where hook use is strongly preferred, the results conform to the predictions concerning *number* for hook use (Configurations a > b = c). Neither the stick solutions in Configurations a, b and c, nor the hook solutions in Configurations d, e and f conformed to any patterns. We might have expected that they followed the complexity of the respective stick and hook affordance structures. But these solutions, being not-preferred ones, were probably too small in number to reveal any pattern. Together with the failures, they are simply a remainder. The variability over the configurations within hook solutions is higher than that between stick solutions. This conformed to the predictions, because the affordance structures for hook use were the more strongly varied in *number* complexity.

Table 9: Results of Experiment 3: differences between number of hook and stick solutions for Configurations a-f.

a) hook use

Configuration	chi-square	p
a vs. b	8.0	s.
b vs. c	0.0	n.s.
c vs. d	10.0	s.
d vs. e	7.0	s.
e vs. f	5.0	s.

b) stick use

Configuration	chi-square	p
a vs. b	7.0	s.
b vs. c	1.0	n.s.
c vs. d	1.0	n.s.
d vs. e	2.0	n.s.
e vs. f	5.0	s.

Note. Significances were tested with the McNemar chi-square Test; s = significant; n.s. = not significant; p for chi-square 2.71, df = 1, alpha = .05, one-tailed test; n = 35.

In order to control for a left-right effect of the orientation of Configurations a -e, the differences in frequency of the left-right orientation were tested separately for hook and stick use with the chi-square procedure for the comparison of two dependent samples. There are no significant differences between the left and right orientation of Configurations a-e, neither for hook nor for stick use (Significances of Chi-square were tested against equal chance; p for chi-square 11.1, df = 5, alpha = .05; n = 35).

Total number of solutions. Differences in total number of solutions compared over Configurations a-f were tested with the McNemar chi-square Test, one tailed (see Table 10). The number of solutions doesn't differ between Configurations a, b and c and it also doesn't differ between d, e and f. But for the a, b, c group these are significantly more solutions than for the d, e, f group. The theoretical differences within a, b and c and within d, e and f are minimal, but between these two groups they are maximal. This result fits the trade-off hypothesis. It could not be explained in terms of neither *number* complexity of hook nor stick solutions alone.

Table 10: Results of Experiment 3: within group differences in total number of solutions for Configurations a-f.

Configuration	chi-square	p
a vs. b	1.0	n.s.
b vs. c	1.0	n.s.
c vs. d	9.0	s.
d vs. e	1.0	n.s.
e vs. f	0.0	n.s.

Note. Significances were tested with the McNemar chi-square Test; s = significant; n.s. = not significant; p for chi-square 2.71, df = 1, alpha = .05, one-tailed test; n = 35

Conclusion

The existence of a stick solution as an alternative to a hook solution has to be taken into account if affordance structures are used to determine the difficulty of our tasks. Our experiments demonstrate that this alternative solution is sometimes preferred, even though it is theoretically more demanding in terms of *kind* of temporal integration. *Kind* therefore seems to be traded off against the other theoretical source of complexity, viz. *number* of affordances to be integrated. The trade-off suggests heterarchical control of the preference for an affordance structure. This, because the factor *kind* could be

identified with a higher level of description of the system than *number*, and the preferences are traded off between these two levels.
The unexpected differences between Configuration d and e from Experiment 1 could now be explained by comparing them to Configurations a and d from the present experiment. In both pairs of configurations, the preference changes from hook to stick. So in Experiment 1 hook use affordance structures must have been dominated in Configurations d and e by stick use ones and this affordance structures influenced the total number of solutions.
The results of Experiment 2 are more crucial than those of Experiment 1 for theories that assume task-specific variations in difficulty resulting from either memory load or processing load. These could somehow be applied successfully to the data of Experiment 1, because they could easily assume load to increase with *number* complexity. *Kind*, however, cannot be understood so easily without taking the causal structure of a possible event into account.

General Discussion

We are aware of the preliminary character of our analysis of complex action. Nevertheless we hope to provide set the initial steps in a discussion on that topic. We started from the assumption that complex actions are guided by perception as described by Gibson's (1979) affordance concept. This view was applied to tool use. For becoming a tool, an object must be handled by an actor in relation to other objects or substances. Tool use therefore was defined as performing an action on a target by performing an action on a tool. The action on the tool is embedded in the action on the target. In order to account for the role of perception in these hierarchically embedded actions, we proposed a higher-order affordance structure concept, with which these actions were regarded as complex events, in which the actor participates. To do so, he should be able to perceive the possibility of realizing a hierarchically integrated structure of mutually constraining complementarities. Besides complementary relationships between actor and environment there are also complementary relationships between objects to be taken in account. In the case of tool use the actor has to manipulate tool-target complementarities in order to reach a certain actor-target complementarity. Each complementarity at lower-order level has a complementary relation to an affordance at higher-order level. The higher-order affordance structure could be said to organize the action. The temporal integration is mirrored in the event structure of action.

We were able to derive predictions regarding the difficulty of tool use in certain configurations from the complexity of the affordance structures involved. Structural and temporal sources of complexity were distinguished. The structural complexity source was specified as *number* of elements to be integrated at a certain level in an affordance structure, the temporal source was the *kind* (diachronous vs. synchronous) of the integration. In our experiments it was shown that the actions of infants and children in tool use were sensitive to both forms of complexity. The difficulty of performing or anticipating tool use in different situations was generally in accordance with the complexity predictions.

Our higher-order affordance structure concept was able to bring the threefold relation between actor tool and target into play, preserving the duality principle. Reduced to three isolated two-fold relationships, it would be impossible to specify the character of tool use as mediated action. A tool is both, an object acted upon by the actor and acting on the target.

With the higher-order affordance structure concept, the object to be identified as tool is constrained by the effectivities of the actor and the target and the desired relation of the actor with the target. This was called the tool function. We argued that the information minimally needed in order to perceive the tool function depends on the event to be produced by action. Therefore the implementation of the suggestion to treat the tool function as a complex affordance structure differs in its consequences from the point of view of Shaw & Turvey (1981) and Kugler, Shaw, Vincente & Kinsella-Shaw (1990). These authors claim that for action there is objective information in form of a unique specification of a situation as needed. In our view, however, whatever information enables action is information for an affordance (see also Costall, 1986 and Van Leeuwen & van Leeuwen, submitted).

Assumptions about temporal and structural integration of affordances into the higher-order affordance structure of the tool allows for possible alternative realizations of it by simply integrating the same components differently. An object sometimes was used as a stick and sometimes as a hook, in order to realize the same goal. The emergence of rival solutions could therefore be used as an argument for the higher-order affordance structure. On the basis of complexity it was possible to predict not only the occurrence but also the preference for one of the possible alternative ways in which affordances had to be integrated.

A restriction on our results originates from the fact that in our discussion of possible alternative explanations, we have entirely focused on an unresolved issue in the previously mentioned literature; viz. the role of spatial contact. Köhler (1917), Bates et al. (1980) and Brown (1990) all suggest that spatial contact between tool and target facilitates the detection of the tool function. But all these authors fail to provide a reason for that. A more specifically described rival account, found in the literature, was the contact hypothesis, which assumed that spatial contact between target and tool makes them being perceived as one object. This was the only explanation from the tool use literature that is sufficently specific to become testable. It was dismissed, however, in Experiment 1 as in conflict with the data. With our description, it was possible to explain why the contact hypothesis works in some cases and breaks down in others.

Yet, other alternatives could be developed in the framework of mental imagery and cognition (Piaget, 1971; Pick, 1988; Shepard, 1984). A principled discussion of their views falls beyond the scope of this paper, because it would require intensive exegesis in order to apply their conflicting insights to tool use and compare them to our views (see Dean, 1990 for a review). We will give here only one example of how our results could provide interesting questions for the issue of mental imagery. Piaget & Inhelder (1971) assume that a qualitative change occurs during development in the structure of mental images. According to their experimental results, children in pre-school age are able to construct initial and sometimes end-states of movements and transformations, but not ordered series of intervening states. The ability to foresee these emerges around seven or eight years. However, our results show that children as young as 2 and 3 years old are able to foresee mediating steps in a proper sequence.

The difference in results could be due to a difference in method. The experimental task in Piagets mental imagery research is imagery itself. Children are asked to imagine (or to draw) how a certain object would look like if it changes its position in a certain way. By contrast, in our tool use task mental imagery could be a means for anticipating an action that is needed to reach an end-state. Probably this kind of paradigm could open new ways of investigating imagery.

Despite restrictions on our results, there are issues that can be clarified already on account of our present results. This regards the work of Bates et al. (1980) and Brown (1990). These authors agree in their view that the ability to use tools is based on cognitive functions which require the mastery of abstract, deep structure rules. Brown argues that transfer is mediated by similarity between situations according to the underlying causal structure even in infancy. She examined in her experiments young childrens' preference for a tool out of a series of objects. These were varied with respect to relevant and irrelevant properties concerning the intended function of pulling. Children selected objects with preference according to properties that afford pulling and not to features irrelevant for the task. She interpreted this result as in support of her view that "even young children show insightful learning and transfer on the basis of deep structural principles, rather than mere reliance on salient perceptual features..." (p.130). For explaining the same results, however, we need assume only that relevant information in the context of this task is picked up and irrelevant information not, or not necessarily. The relevant information, i.e. the higher-order affordance structures, however, is not necessarily less perceptual than the irrelevant one; a consequence of our view is that the effort to distinguish between salient perceptive features and a deeper, cognitive structure becomes meaningless.

The relevance of Brown's work lies in showing that, contrary to assumptions in earlier literature (Duncker, 1945; Gick & Holyoak, 1980), even very young children are capable of transfer. This is valid, provided that the principles involved are part of the child's practical experience. From our results we would argue that what is called "transfer of a cognitive rule" (Brown, 1990) is merely the perception of the same affordance structure in all situations varying over action irrelevant properties. A child solving the tool use task in one of the configurations from Experiment 1 may be unable to perform the next one if this requires a more complex affordance structure. But she will be able to solve all situations which require the same or a less complex affordance structure (but e.g. with different colour or texture of the attributes). For these configurations we observed what could be called "transfer". In this sense transfer is a measure of what is perceived and depends on the complexity of affordance structures needed in order to act successfully. As shown in our experiments, children seem to be able to perceive less complex affordance structures earlier in development than more complex ones. Transfer can only occur with respect to affordance structures subjects already are capable of perceiving. This could explain why age dependency was found for transfer learning.

Mastery of tasks in our view is context-bound, because no abstract rules are being learned. Action is determined by grasp of a specific affordance structure sufficient for solving a specific tool use task. For instance, if an affordance structure (e.g. involving a hook-target relationship) is already realized, there is no need to take it into account. The child can just exploit the given relationship, without being aware of it. Another illustration of this sufficiency principle is the tool use behaviour observed most early in development, viz. pulling a string attached to an object (Bates et al. 1980). Here, it is obvious that the child doesn't need the information how this complementary relationship between string and target was realized. Independently of what the actor does, the string remains attached.

Knowledge of an underlying causal structure, such as the physical laws guiding solid objects that keeps the rope attached to the string is not necessary, in our view, to perform this specific task. Clearly, it is not sufficient either. We assume that the grasp of the affordance structure specific to that situation is sufficient. On the other hand, the higher-order levels of the affordance structures may be less context bound than their lower-order arguments This suggests that a higher-order structure could ultimately be used to describe embodied knowledge of a law.

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Appendix 1

observation categories:

reaching: stretching the arm towards the target

success: obtaining the target independently with the hook

success by using the hook as hook: the target is within the crook part of the hook

success by using the hook as stick: the target is in contact with the hook, but not at the crook part

Appendix 2.

Results of Experiment 1: Within group differences in success for the half-way group.

Configuration	chi-square	p
a :b	2.0	n.s.
a : c	10.0	s.
b : c	8.0	s.
c : d	5.0	s.
d : e	4.0	s.

Note. Significances were tested with the McNemar chi-square Test; s = significant; n.s. = not significant; p for chi-square 3.84, df = 1, alpha = .05; n = 35; two-tailed test.

Appendix 3

Results of Experiment 1: Differences in success with or without a model for Configurations a-e for the half-way group.

Configuration	chi-square	p
a	11.0	0.01
b	7.0	0.01
c	6.0	0.05
d	3.0	n.s.
e	-	n.s.

Note. Significances were tested with the McNemar chi-square Test; s = significant; n.s. = not significant; p for chi-square 3.84, df = 1, alpha = .05; n = 35; two-tailed test.

CHAPTER 3

Developmental aspects of perceiving higher-order affordance structures

Developmental aspects of perceiving higher-order affordance structures

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The concept of higher-order affordance structures was introduced in earlier studies as a means to describe development in the perception of tool functions. Higher-order affordance structures are a means to control the temporal integration of lower-order affordances/complementarities in complex action. The complexity of the integration according to the description was used to predict the preference for a tool function. In order for this concept to form the basis of an account of development, it is of importance that the criteria for complexity are unaffected by age and task variation. These predictions are put to a test in the present study.
Three experiments were performed in order to test preference predictions from complexity for different age groups and tasks. Experiments 1 and 2 showed that preferences remain invariant accross age. Experiment 3 showed that preferences vary in accordance with complexity predictions, across tasks of which the surface properties are similar, but the functional relations differ. Some phenomena from literature were discussed, concerning tasks that require the selection of one object for the manipulation of another. It was argued that complexity of higher-order affordance structures could, in principle, explain these results.

Introduction

Humankind is characterized by extensive tool use. The emergence of tool use enables the child to overcome the limitations on her action capacities resulting from her endowment. The acquisition of tool use in early childhood therefore is an important phase in development. Tool use may begin as trial and error. At some point in her development, however, the child acquires the capacity to plan the use of an object as a tool. This capacity requires, among others, the ability to perceive the *tool function* of that object.
A framework for describing the perceptual requirements at this level of performance was proposed in van Leeuwen, Smitsman, & van Leeuwen (submitted). The investigation was based on the ecological approach to perception as founded by James Gibson (1966;1979). While in this approach perception is assumed to anticipate

action, action constraints are mirrored in perception. The functional meaning of objects and events is available to the perceiver in the ambient array of light. "Affordances of a given place in the environment establish for an individual what actions are possible there and what the consequences of those actions are" (Heft, 1989, p.3). Affordances describe a potential relationship between properties of the environment and those of an individual perceiver. For example, graspability is an affordance of an object, which describes a complementary relationship between physical properties of that object (e.g. its size) and biomechanical properties of the actor's "grasping system" (e.g. handspan). This means that one object can afford graspability to an adult person but not to a child because the object is e.g. too big to be grasped. Affordances thus are properties of the environment scaled in reference to an individual.

Affordances of tools are special cases in so far as a complementarity between actor and tool-object can only be a *tool* affordance, if complementary relations between actor and target and between tool and target are taken into account. A hammer as a tool is chosen e.g. in order to hammer a nail into a wall and not just for hammering. The hammer must be light enough to handle but at the same time strong enough to drive the nail. As argued extensively in van Leeuwen et al. (submitted), the interdependence of these relations themselves is of importance for the tool function and therefore must be perceived by an actor. The weight of the hammer determines how it can be handled and also how much force the actor can and must employ in order to drive the nail.

To describe such constraining relationships between complementarities, it was assumed that at first-order level there are affordances which are akin to the ones familiar from Gibsonian literature. Additionally, at first-order level there are complementary relationships between objects, such as tool and target. Because there is no actor involved we cannot call them affordances. We instead referred to them merely as complementarities. With these as basis, a concept of *higher-order affordance structures* was introduced. The definition is recursive, allowing first-order affordances, second-order affordance structures, third-order ones etc. The higher-order affordance structure concept is an extension of the traditional affordance concept. As will be illustrated, it could be applied to describe the interrelatedness of lower-order complementarities, needed to describe the role of perception in complex actions such as tool use.

What makes an object a tool is its subordination into a hierarchically organized action (Greenfield, 1991; Werner, 1957). The subordination has a structural and a temporal aspect. Structurally, affordance structures of tools consist of a nested structure of complementary relationships between actor and environment and between objects in the environment. In order to realize the goal of the action, these complementarities must be placed in an appropriate temporal organization. Whatever has to be realized first is subordinated to the goal which is realized last. Therefore an actor on a global level has

to envisage the event in its entirity. The higher-order affordance structure specifies the tool use action as a nested event structure.
Experiments reported in van Leeuwen et al. (submitted) illustrated the applicability of the higher-order affordance structure concept. In these experiments, young children were presented a hook as tool to obtain a distant object. Configurations a-e in Figure 1 were subsequently presented, consisting of a tool and a target. The initial spatial position of the tool with respect to the target varied. It was shown that the difficulty of perceiving the tool function was not dependent on the relative spatial position of tool and target per se, but on the complexity of the higher-order affordance structure.

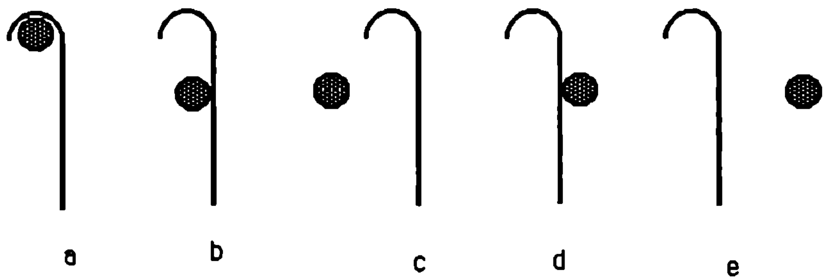


Figure 1: Configurations used by Van Leeuwen, et al. (submitted).

The present study investigates the possibility of applying the higher-order affordance structure concept within an account of human development. Perceptual development was characterized by E. Gibson (1988) as a process of increasing differentiation of relational properties of actor and environment. More and more specific actor-environment relationships emerge and become integrated in a hierarchical structure of increasing depth. We aim at specifying this as the capacity to perceive increasingly complex higher-order affordance structures. Such a view on development requires that the criteria for "complexity of a higher-order affordance structure" remain invariant over age. Therefore the study of the generality of our complexity criteria is directly motivated by our interest in child development.
Three sources of complexity of higher-order affordance structures were proposed in van Leeuwen et al. (submitted). One source of complexity regards our most general

assumption, the *order*, which refers to the depth of nesting of a higher-order affordance structure. It is illustrated by the fact that tool use in general is a complex action that occurs relatively late in development. In our view, this is because tool use requires the integration of complementary relationships between actor and tool, actor and target and tool and target. Therefore, this form of complexity may be useful for distinguishing tool use from other behaviours. In our present study, however, we wish to compare different tool use configurations for their complexity.

For doing so, two other sources remain, which parallel the distinction between structural and temporal integration within an affordance structure of a given order. One referred to the *number* of lower-order affordances to be assembled into a higher-order structure. E.g. in Configuration d of Figure 1, an actor has first to flip over the hook and to bring the hook in spatial contact with the target within the crook part of the hook before he can realize the tool function which is pulling the target within reach. For Configuration a in Figure 1, however, just pulling the hook is enough for obtaining the target. The difficulty of perceiving the tool function was assumed to be proportional to the number of complementary relationships to be integrated.

The other source refers to the *kind* of temporal integration of lower-order affordances into a higher-order affordance structure. Diachronous and synchronous *kind* of integration were distinguished. Intermediate forms were admitted. Diachronous means that different complementary relationships can be realized sequentially, one by one. In contrast, synchronous integration requires the realization of different complementarities in parallel. Parallel realization of different relationships requires more extensive control than realization one by one. E.g. hook use in Configuration e realizes the different relationships to obtain the target in sequence, diachronously; first the crook is placed in the proper position for pulling. While pulling, the position of the target is maintained by the crook itself. But consider a solution of the same task by using the tool object as a stick; by using it directly to move the target towards the actor and at the same time preventing it from sliding away from the present point of contact with the tool. The, relatively, simplest way to combine these requirements is a circular, sweeping movement of the tool.

Development in our view requires growth in ability to assemble increasingly complex affordance structures. The seemingly small variations in configurations between Configurations a-e in Figure 1, affected the complexity of the affordance structures. As a consequence, children able to solve the theoretically easier configurations were still unable to solve the more difficult ones. But once a child was able to solve a certain configuration, all the easier ones could be solved too.

Van Leeuwen et al. (submitted) distinguished three groups of children. Children in the youngest group (9 to 12 months) ignored the tool object and instead just tried to reach

for the target. For a group between 14 and 24 months old, the ability to perceive the tool function in different configurations depended on the relative spatial position of hook and target (see Figure 1). They failed in configurations of which the higher-order affordance structures contained a large number of lower-order ones and succeeded in the configurations which required a lesser number. The oldest group from 25 months up to 3.8 years succeeded in all configurations. It was concluded that at least children who are in the course of learning tool use are sensitive to these complexity sources.
But, strictly speaking, these results could not be generalized to the older group. Percentages correct were caught between a floor effect (the youngest group unable to use the tool) and a ceiling effect (the older ones solving all the configurations). Measuring percentages success, leaves no possibility to check if subjects who solve all tool use configurations still might have experienced the difficulty of the configurations in accordance with their theoretical complexity. Preference studies, however, provide this possibility. We may predict the preference among two possible actions, which both lead to the realization of the actors goal. We expect that the solution will be preferred that imposes the least complex affordance structure, even if subjects could easily perform the action that leads to the realization of the more complex affordance. In addition, the strength of the preference is expected to be proportional to the difference in complexity between the alternatives.
In our view, the description would be of little value, however, if it applies only to subjects who are in the course of learning to use tools. Therefore the first purpose of this article is to investigate if the description applies to different age groups. We will report two experiments, studying the preferences among alternative solutions for different populations of older children, who could be assumed to be able to use the tools in Congifurations a-e successfully.
Another issue concerning the generality of our description is, whether it also applies to other tool use tasks than those of van Leeuwen et al. (submitted). This was investigated by using the configurations from Figure 1, but a different task. Changing the task means that some complementary relationships between actor, tool and target that were irrelevant before now become relevant and vice versa. Therefore, the preferences should change accordingly. By contrast, if only surface, task-unrelated (e.g. geometrical) properties of the configuration would determine its complexity, we would expect unchanged preferences accross tasks.
This study on the generality of the higher-order affordance structure concept will be completed by presenting some previously unresolved issues from tool use literature together with our explanation and by showing how some tasks from diagnostic tests on development of manipulative action capacity could thus be interpreted.

Experiment 1

Introduction.

Tool use configurations were constructed, each consisting of a hook and two identical targets. The configurations are combinations of ones from Figure 1. In this way only one solution is possible at a time, but there is a choice between two alternative solutions. This allows the study of preference for a solution. It was expected from the affordance structure hypothesis that children will prefer the solution which is theoretically least complex. Moreover, the strength of preference was expected to be similar to the percentages solution for these configurations for the younger children in our earlier experiment.

For the configurations in Figure 1 complexity was predicted in van Leeuwen et al. (submitted) as the result of a dynamical interplay of the complexity sources *number* and *kind*. Both affected the percentage correct for younger children in the previous experiment. They were traded off against each other; the synchronous solution was sometimes preferred if it was more parsimonious in terms of number. Therefore, both number and kind complexity had to be taken into account. For a specification of these complexities for all configurations, see Appendix 1. According to the theoretical differences in task complexity and the earlier results we expect the following preferences: Configuration a > b > c > d > e.

The chosen method of using only one hook and two targets for a trial prevents the presentation of the complete set of 10 possible pairs out of Configurations a-e from Figure 1. There are no trials comparing Configurations a, b, c and respectively Configurations d and e to each other directly. These configurations can be compared indirectly by comparing preferences of Configurations a, b, c with respect to Configuration e or d in isolation. Only in this way could preference data be obtained. It was, for instance, impossible to use two hook-target configurations simultaneously and let children choose the preferred one. Three to four years old children became confused by those choices because there are too many things to be compared. Usually they grasped both hooks and tried to obtain the targets, which failed. Presenting one hook only makes a comparison more implicit to performance. The age group 3 to 4 years old is especially of interest for us because this group was successful in performing all configurations in the previous experiment.

A still older group of children who are able to perform the preference task even with two hooks was tested in Experiment 2. For this group the whole set of possible pairs out of Configurations a to e in Figure 1 was presented.

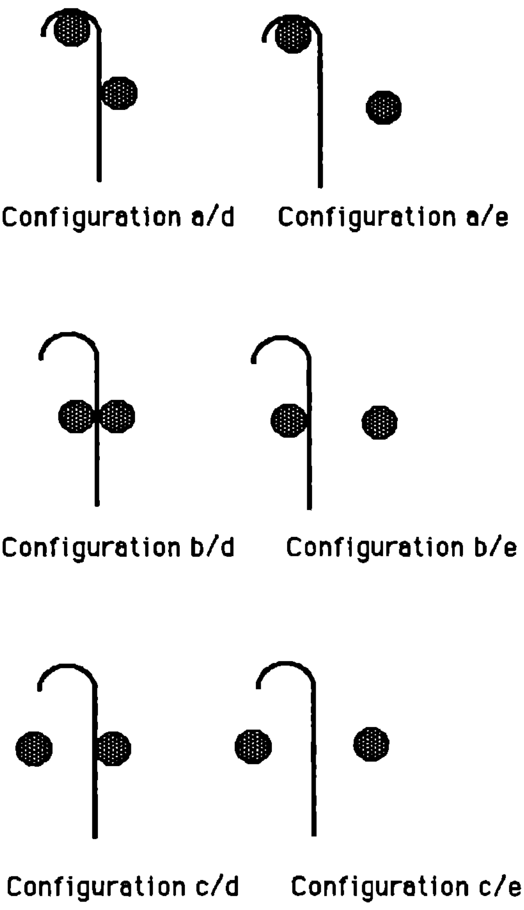


Figure 2: Configurations used in Experiment 1.

Method

Subjects. Twenty-eight subjects in the range of 3;0-5;0 years of age participated in the experiment with their parents' consent.
Stimuli. The six experimental tool use configurations from Figure 2 were used. To each configuration corresponded a mirror-image variant, which could be obtained from the Figures by reflecting them around the vertical axis. This variation is indicated as left-right orientation of the hook.

Material. Plastic hooks were used as tools, about 60 cm long, approximately 12 mm cross-section and with a weight of 75 g. Targets were three different pairs of identical rubbery animals, about 10 cm in diameter. The experiment was performed at a 1.20 X 2 m table adjusted to normalize children's location. Children were standing in front of a table on a flag-stone which marked the middle position. The whole setting is shown in Figure 3.

Procedure. Each child was first allowed to explore the hook in order to become familiar with it. The experimenter asked the child if it would like to have a cookie. None of the subjects refused, so as a next question, the experimenter asked, putting a cookie out of reach for the child on the otherwise empty table: "can you reach this cookie?" If the answer was negative, appropriately, the experiment continued; if the child gave an affirmative answer, the experimenter encouraged the child to obtain the cookie, until it was clear that it was impossible for the child to do so. The experimenter gave the hook to the child and asked: "now can you do something to make the cookie come to you?" After an affirmative answer given by each child, the child was allowed to do so by using the hook. This cookie was laid apart for the child, within its reach. In the experimental phase following, as target three pairs of respectively two identical rubbery animals were used. Each trial began with distracting the child with a picture book. Meanwhile, one of the configurations from Figure 6 was placed on the table by the experimenter. The child then was allowed to use the hook to bring one of the animals within reach, making sure not to interfere with the child's choice. All children thus were presented all six experimental configurations in random order. Left-right orientation of the hook was alternated within subjects, and balanced between them. For all subjects each of the three pairs of rubbery animals was used for two times, randomized over targets.

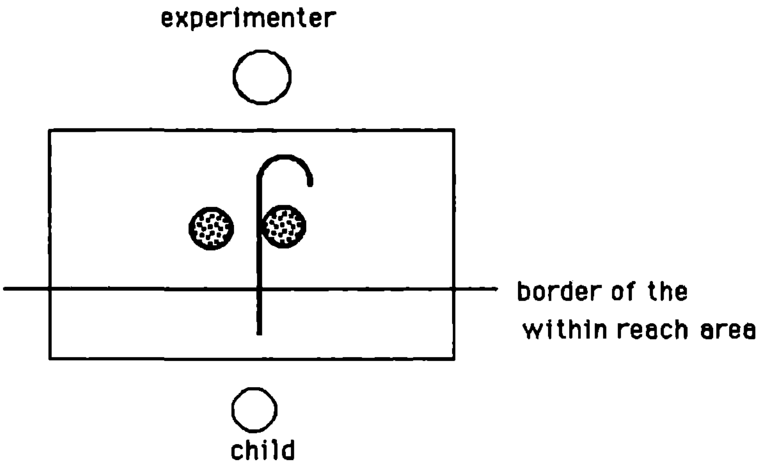


Figure 3: Experimental setting used in Experiment 1

Results and discussion

As shown in Table 1, the order of observed preferences is perfectly in accordance with the theoretical expected order. This may suggest that subjects capable to solve all configurations, also have a preference according to the theoretical complexity of the affordance structures.

Significances of differences in preference per configuration were tested with a one-group Chi-square test against equality. Except for Configuration c/d the differences for all configurations where significantly different from equality (see Table 2).

Table 1: Results of Experiment 1. n = 28.

Configuration	Preferences		
	Expected	Observed	Observed Percentages
a/d	a	a	89.5
a/e	a	a	96.4
b/d	b	b	78.5
b/e	b	b	89.5
c/d	c	c	69.6
c/e	c	c	75.0

Table 2: Results of Experiment 1. The columns contain for every configuration the frequencies of realization of the two alternatives; the expected frequency for equal preference; the chi-square for df = 27; the significance level of the chi-square test against equal probability of realization

Configuration	part	observed frequency	part	observed frequency	expected f for 50%	chi-square df = 27	p
a/d	a	25	d	3	14	17.29	.0001
a/e	a	27	e	1	14	24.14	.0001
b/d	b	22	d	6	14	9.14	.0025
b/e	b	25	e	3	14	17.29	.0001
c/d	c	19	d	8	14	3.57	.0588
c/e	c	21	e	7	14	7.00	.0082

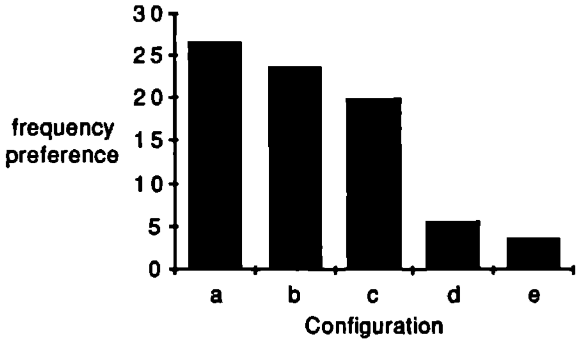


Figure 4: Experiment 1. Mean percentage preference for Configurations a to e, calculated from pairwise choices.

An additional result is that the preference for Configuration a is stronger than for Configurations b and c when paired with Configuration d. The same holds for the preference relations of Configurations a, b and c compared to Configuration e (see Table 2).

In sum, differences in preference are obtained in accordance with differences in integration demands.

The results indicate that the preferences of older children are in accordance with what was easier for the younger children. Therefore, not only children in the process of learning to use tools act in accordance with the complexity of the respective affordance structure, but also the older ones.

Differences in preference between Configuration a,b and c and respectively between Configuration d and e can not be tested directly. A preference comparison between all possible pairs out of Configurations a to e would be important in order to confirm the results of this Experiment.

Yet, it could be argued that still older, more skilled children no longer perceive differences between configurations in terms of our affordance structures. For them performing such hook tasks seems much more automaticly. Differences between configurations should not be noticed. Therefore, Experiment 2 is performed with a still older group of children.

Experiment 2

Introduction, hypothesis

The present experiment examined children in primary-school age. Instead of letting them perform the task (which we thought these children could safely be assumed all to be capable of), we asked them to choose between two configurations. Subjects have to made their decisions on the basis of anticipation. As shown in experiments by Carello, Grosofsky, Reichel, Solomon & Turvey (1989) people are able to anticipate actions depending on the constraints given for the action system. Following ecological realism, we assumed that perceiving an object as a tool is a task of anticipating the act of tool use. If this is the case, we expect judgements to correspond to the preferences and percentages correct in the experiments of van Leeuwen et al. (submitted), where tool use was actually performed.

Theoretical preferences can be determined from the differences in complexity of the affordance structures involved. Accordingly, Configuration a in Figure 1 is predicted to be always preferred because the affordance structure involved is least complex compared to all remaining configurations. Configuration e is expected never to be preferred because the solution requires anticipation of the most complex affordance structure. The configurations b-d are predicted to be preferred whenever they are presented in combination with a more complex one. Thus, when every Configuration a-e is combined with each of the remaining four, the predicted percentage success for each configuration follows from the order in complexity between their affordance structures given in Experiment; see Figure 6. (E.g. Configuration b is predicted to be prefered three times out of four; Percentage preference thus is 75%.)

Method

Subjects. The experiment was run in 2 schools in the Dutch town of Breda. Fourty children between 6 and 7 years old, 19 girls and 21 boys, volunteered for the experiment.

Stimuli, material. From the five configurations shown in Figure 1, at most ten different pairs can be formed if the order within a pair is not considered. These pairs of configurations were included as stimuli in the experiment. Unlike in Experiment 1, where two configurations were combined, they were kept separate here. One configuration was presented in the left-hand position of the child and the other at the right hand side. The two configurations were displayed at a distance of 30 cm from each other. Right and left position of a configuration in a pair were balanced across subjects. Also the orientation of a hook to the left or right side was balanced over subjects. The materials used were similar to those of Experiment 1. Targets were cookies. Children were standing on a flag-stone which marked the middle position. The whole set-up is shown in Figure 5.

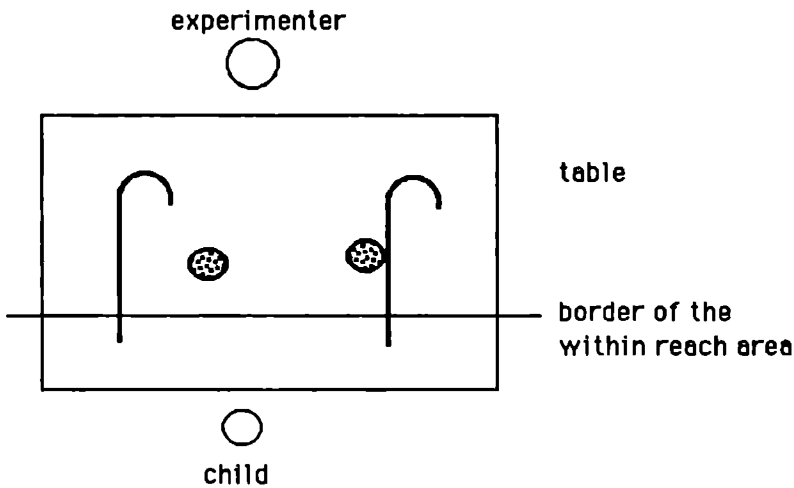


Figure 5: Experimental setting used in Experiment 2

Procedure. At first the experimenter asked: " Do you want to have a cookie?" After the child's response "Yes", the experimenter announced a game and started with the first trial. The child was asked to turn 180 degrees on the spot, so that he or she no longer could see the display on the table. A pair of configurations from Figure 2 was installed on the table. Then, the child turned back and the experimenter asked: "Can one of these cookies be made to come to you? For which of these two will it be easier?" The child chose one of the configurations by saying or pointing. The choice was registered by the experimenter. Ten of these trials, including all possible pairs out of Configurations a to e in Figure 1, were presented to a child in a random order. After the last trial the child was allowed to actually use the hook to get the cookie. Because the trials were presented in random order, the last trial was randomly selected from the ten possible pairs. The result of this actual attempt was also registered by the experimenter. Children who did not succeed in getting the cookie on their own by using the hook after the last trial were given one.

Results and discussion

Surprisingly, 11 out of the 40 children didn't succeed in obtaining the cookie with the aid of the hook after the last trial. The preferences of the children who obtained the cookie on their own after the last trial (successful group) and those who didn't (unsuccessful group) are presented separately.

Figure 6 shows the preferences of the 29 children who got the cookie on their own (successful group) compared to the theoretical preferences.

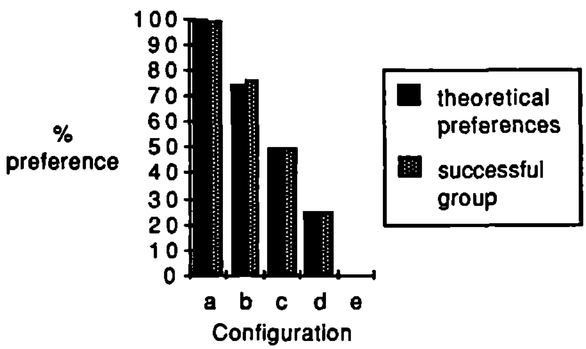


Figure 6: Results of Experiment 2. Percentage preference for Configuration a to e as obtained from the theoretical description compared to the observed preferences for the successful group.

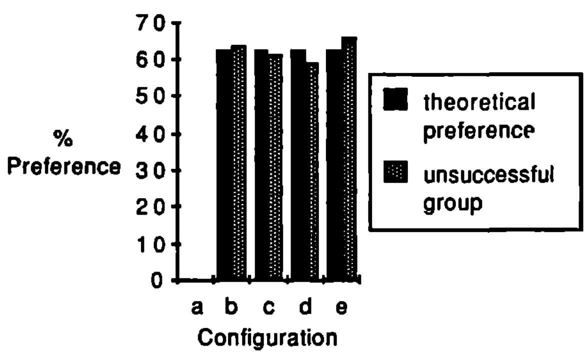


Figure 7: Results of Experiment 2. Percentages success in Configurations a-e for the theoretical predictions concerning the act of reaching the target without tool compared to the unsuccessful group.

As shown in Figure 6, the preferences are as predicted on the basis of differences in task complexity. A linear regression analysis between the estimation values of the successful group and our hypothetical predictions gives a prediction value of $r^2 = 0.98$.

In fact, the preferences are not only highly consistent with this hypothesis averaged across subjects, but also the total number of violations of the hypothesis in concrete choices is extremely low. Out of the total number of 290 choices made by the children, the total number of violations is 2. We conclude that for children in the successful group, the differences in task complexity determines the child's preference for a configuration.

In van Leeuwen et al. (submitted), we obtained percentages solution for the group of children 14 to 24 months old, according to: Configuration a = b > c > d > e. The lack of a difference between Configuration a and b, was interpreted as a ceiling effect. This interpretation is comfirmed by the fact that Configuration a is preferred stronger than Configuration b compared to Configuration d or e respectively in the present experiment. Again, in Experiment 2 a difference is found between Configurations a and b according to our theoretical prediction. In view of the stability of results over experiments, we may interprete the difference as confirmation to our assumption of a ceiling effect as responsible for the lack of difference between the two configurations in our earlier experiment (van Leeuwen et al. submitted).

In Figure 7, the preferences are shown of the group of 11 children who, suprisingly, were unable to get the cookie by using the hook after the last trial (unsuccessful group). Configurations b to e were equally preferred and Configuration a was never preferred. These preferences conform to what might be expected in reaching without tool. Theoretically, Configurations b to e are equal with respect to the act of reaching because the target is always equally far from the actor. In the case of preferences concerning reaching, Configuration a is theoretically never prefered. This, because the distance between target and child is larger in comparison with the other configurations (see Figure 7).

We predicted the preferences as detrmined by the act of reaching for the target without tool.The prediction value from a linear regression analysis is $r^2 = 0.98$. Children of the unsuccessful group failed to take the hook into account.

There are many possible reasons why these children might act according to the reaching hypothesis. Children between 6 and 7 years old can safely be assumed to be able to use tools in this type of situation. In a more familiar configuration or after a demonstration they would have no problem at all in doing so. Our results may be due to the kind of task where children lack feedback from performing the act of tool use or due to an inhibition, perhaps caused by their interpretation of the instruction as requiring them not to do the obvious, viz. to use the hook. With regard to our hypothesis, however, it is irrelevant why they refrain from doing so. Individuals prefer configurations according to the action anticipated, either with the tool or without it.

Results from the group using the tool for obtaining the cookie in the last trial are the same as for experiments with younger, successful children. So, independent of age and differences in task, the theoretically described task complexity seems to predict action.

The question could be raisedwhether the same sources of complexity are relevant for children who are able to perform successfully in all configurations as for those who are in the process of learning to use tools. Its relevance lies in showing that the lower-order affordances children use when they are in the process of integrating their perceptions, are still available when the integration is completed. Lower-order affordances can be useful maximally efficiently if they can be embedded in a wide variety of higher-order affordance structures. The ability to perceive the graspability of a spoon can be useful in eating but also in stirring or play. If this lower-order affordance is available separate from the higher-order affordance structure it is embedded in, the actor may profit from its familiarity. Along similar lines, in Gal'perin's (1969) model of the formation of mental acts, mental development results from meaningful material activity. The basic mechanism of ontogenesis is the mechanism of interiorization, whereby the forms of society transcend to the mental level of the individual (see also Vygotskij, 1986).

Abstraction through language means that action relevant properties of an event are described so that they can be applied to other events varying in irrelevant properties. We do not agree with Gal'perin's notion that language is assumed to be the only means available for abstraction. The higher-order affordance structure concept assumes that abstract information can be perceived directly. "Gibson's crucial proposal in the theory of affordances is that we typically, and primarily, attend to the higher-order invariant information which specify what objects afford for our action, rather than the lower-order information which specifies its isolated properties. We simply can see that a surface affords walking"(Costall, 1981 p.46).

Gal'perin's claim of reconstructability of the invariant properties of a material act is important with respect to communication as he noted. Reconstructability is also needed in order to act flexibly upon changing environmental and bodily circumstances. In order to use relational information available flexible, lower-order affordances should be consciously distinguishable. Cognitive as well as motor skills are assumed to be integrated as subroutines or components into hierarchical organized wholes (Bruner 1973; Fischer 1980; Werner, 1957). For the aquisition of new skills, already available, integrated ones, are needed. Available components or subroutines could be integrated in a different way into a new skill. In order to make use of them, it is neccessary to isolate

them from their hierarchical context. As an example, consider the task of solving Configuration e from Figure 1 for an adult subject. The different complementary relationships between tool and target to be realized are integrated into a smooth action by a skilled subject. Looking at the action it is difficult to isolate the different components. Consider the same subjects confronted with the problem to get something out of reach, and there is no object available to be used as a tool. The person than could solve the problem by making a hook. Making the hook requires explicitly the recognition of the components of the act because they constitute the properties of the potential tool. As an example, the lenght of a hook to be made must be determined by the distance to be covered but also from the requirement that the actor must be able to manipulate it. Both relationships must be recognized in order to integrate them later into a smooth action.
In order to demonstrate how lower-order affordances should be integrated in new actions, we performed experiment 3.

Experiment 3

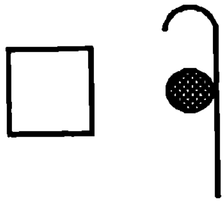
Introduction

An important characteristic of the affordance structure concept is its relational nature (Heft, 1989). Perception is the result of interaction of organism and environment. Concretely in our experiments, perception of the tool function is assumed to result from an interaction between the actors goal, his biomechanical properties and properties of the respective tool-target configuration. This implys that perception is not predictable from the environmental properties in isolation. A consequence of this view is that the relative difficulty of tool use configurations depend on the goal of the action. In Experiment 3, an attempt is made to investigate more directly the dependency of the perception of the configurations on the goal of the action.We try to discover whether the rank order in difficulty obtained in Experiments 1 and 2 could be completely turned over by changing the goal. The configurations used in Experiment 3 are shown in Figure 8. The hole in the table on which a configuration were presented is novel in comparison with the configurations of Figure 1. The goal now is to push the target (a plastic duck) with the aid of the hook into a hole in the table, in order to plunge it into a water-basin. In Configurations 1/2 and 5/6 the position of target and tool relative to the hole is such that it is possible to move the target directly towards the hole, whereas for Configurations 3/4 and 7/8 the position of the tool must be changed first. Configurations 1-4 in Figure 8 are instances of Configuration b from Experiment 1 and Configurations 5-8 are instances of Configuration d from Experiment 1. Mirror images of every configuration are included (Configurations 2, 4, 6, 8).

According to the results of Experiments 1and 2, Configuration b was easier than Configuration d. This is expected to be overthrown by the new goal. Table 3 shows that different instances of Configurations b and d may have become equal in difficulty, if their affordance structures related to the new goal are similar in complexity. This is the case for Configurations 1/2 and 5/6 compared to Configurations 3/4 and 7/8 respectively. On the other hand, differences in difficulty are expected among different instances of Configuration b due to the changed affordance structure related to the new goal. This is the case, between Configurations 1/2 and 3/4, where the latter is more difficult. Likewise for the variations of Configuration d, where Configurations 5/6 may be expected to be easier than Configurations 7/8.

Table 3: Theoretical predictions of relative differences in percentages success for Configurations 1 - 8 with respect to Experiments 1 and 2.

	Experiments 1/2	Experiment 3
Configuration	1/2 = 3/4	1/2 > 3/4
Configuration	1/2 > 5/6	1/2 = 5/6
Configuration	5/6 = 7/8	5/6 > 7/8
Configuration	3/4 > 7/8	3/4 = 7/8



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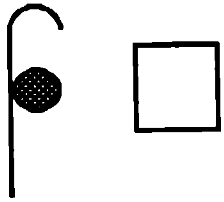

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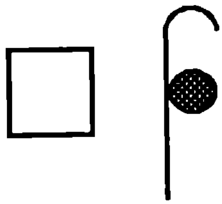

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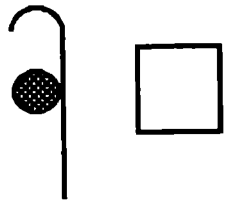

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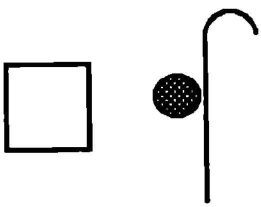

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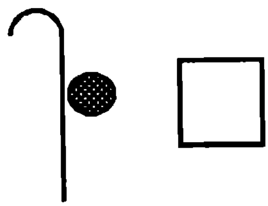

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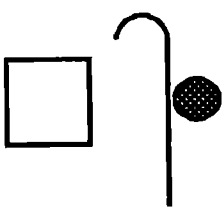

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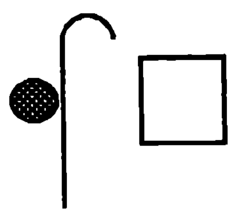

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Figure 8: Tool use configurations of Experiment 3

Method

Subjects. The experiment was run in three child day-care centers in the Dutch towns Nijmegen and Wijchen. Twenty-nine children between 17 and 32 months old(16 males and 13 females) volunteered with their parents' consent.

Material. The same plastic hooks as in the former experiments were used. The target objects were three plastic ducks, each of a different colour, about 10 cm in diameter and about 4 cm in height. The table used for the presentation of the configurations was 70 cm in hight. Part of the surface of the table consisted of a disk, 70 cm in diameter (see Figure 9) which could be rotated by the experimenter. Within the disk there was a circular gap of 12 cm in diameter. Under the table a basin filled with water was placed, in which the duck plunged whenever it fell through the hole.

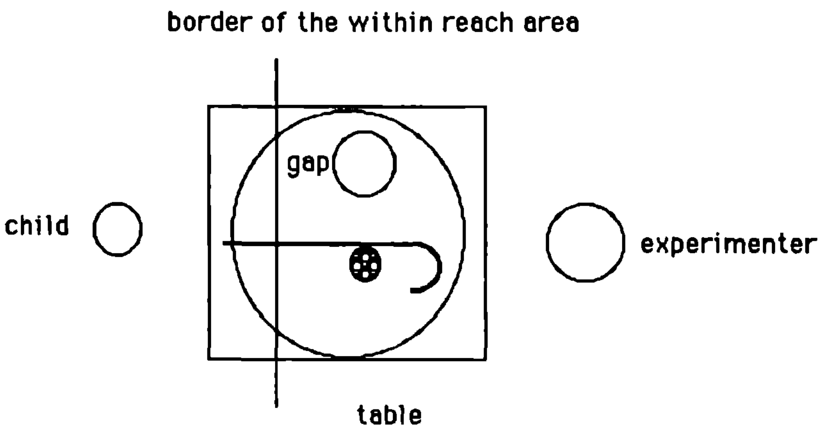

Figure 9: Experimental setting used in Experiment 3.

Stimuli. Every subject was presented with 4 configurations, one out of Configuration 1/2, one out of Configuration 3/4, one out of Configuration 5/6, one out of Configuration 7/8. The configurations were chosen in such a manner that every subject received an equal numbers of configurations with the hole on the left as on the right of tool and target. The order of configurations chosen was randomized over subjects.

Procedure. The experiment consisted of two phases. Phase one was a familiarization phase. The child came into the experimental room with the nurse or mother. Mother or nurse sat down in front of the table with the child on her lap. For about two minutes the hook was given to the child in order to explore it. Even so the three ducks were given to the child for a short time. Then, a nonexperimental Configuration was presented (Configuration a from Figure 1) and the nurse (or mother) performed the act of pushing the duck into the gap with the aid of the hook. Then the child was shown the swimming duck in the basin and he or she was asked if he would help the other ducks to come into the water. If the child agreed, phase two was started. The nurse or mother was asked to prevent the child from climbing on the table or walking around the table in order to put the duck by his or her own hands into the gap. Further she was instructed to behave neutral with respect to the tasks. Four different configurations were subsequently presented to the child. If a child didn't succeed in performing the task after trying four times, the training configuration was presented in order for the child to regain motivation. After each trial, the child was allowed to look at the duck in the basin.

Results and discussion

Within-group differences in success for Configurations 1-8 were tested with the Mc-Nemar chi-square procedure (see Table 4).

As shown in Table 4, the relative percentages of success for the different configurations are in accordance with our hypotheses. The frequencies of correct solution showed no effect of trial number, indicating the absence of an effect of practice. The difference between left and right orientated mirror image configurations was significant only for Configuration 3/4 ($t_{27} = 2.687$, $p = .019$). More correct solutions were obtained with the target at the right-hand.

Table 4: Results of Experiment 3.

expected relation between Configurations	observed relation between % success of these Configurations	chi-square	significance level
1; 2 = 5; 6	100% = 96.6%	1.00	n.s.
3; 4 = 7; 8	72% = 82.8%	3.00	n.s.
1; 2 > 3;4	100% > 72%	8.00	0.05
5; 6 > 7; 8	96.6% > 82.8%	4.00	0.05

Note. Significances with the McNemar chi-square Test; n.s. = not significant; p for chi-square 3.48, df = 1, alpha = .05, one-tailed test; n = 29.

The results support our claim that the relative difficulty of tool-use configurations cannot be explained from the tool-target relationship in isolation. The tool-target relationship has different action implications within the context of different goals.

Examples from the literature

In order to test the general validty of our concept we have to apply the description to a wider range of tasks. We searched the literature for tasks that like tool use manifest themselves in manipulative action, and are concerned with relating more than one object to the actor and to each other. This, because in our view a broad underlying tendency could be observed in the transition to these forms of action during the second year of life. A prerequisite for this claim is, that our approach applies to these forms of action.

Richardson (1932) investigated in detail what determines the difficulty of a tool-use configuration in infants aged from 28 to 52 weeks. Inspired by Köhler (1917) she used several tool-use configurations like the ones shown in Figure 10 in which there are a lure out of reach, with a string attached to it, and also two loose strings. The task is to obtain the lure by pulling the proper string. The observed difficulty of pulling the proper string increases from Configurations A to B and from B to C. Richardson points out that "The relative difficulty appears to depend,..., on the directness with which the loose strings lead toward the lure" (p.311). This explanation holds only for the difference between Configurations A and C and the difference between Configurations B and C, but not for the difference between Configurations A and B.

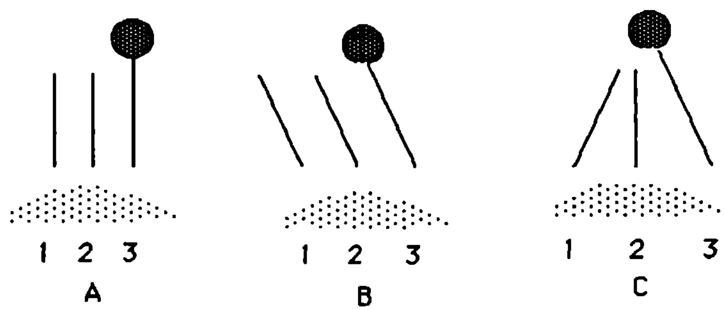

Figure 10: Configurations used by Richardson (1932)

In terms of our theoretical description the differences between Configurations A, B and C would have to be explainable from the differences in complexity of the affordance structures involved. Intuitively, Configuration A is easier than Configuration B. This is in accordance with our description. In Configuration A, String 3 is ready for pulling towards the child (downwards in the picture), whereas the string must be brought in the appropriate orientation first in Configuration B. As compared to Configuration A Configuration B is more difficult. This is so because the *number* of complementary relationships between actor tool and target to be anticipated is increased compared to Configuration A. The same holds for Configuration C if we consider the attached string in isolation, apart from the solutions suggested by the detached strings. In Configurations A and B the detached strings don't suggest different solutions. However, in Configuration C, which is still more difficult than Configuration B this is the case (see Table 3). String 2 in Configuration C suggests the easier solution from only vertical pulling whereas in Configuration B there isn't such a suggestion. Because we assume that less complex solutions will be preferred by an actor we would predict the probability of pulling the wrong string in Configuration C as higher as compared to Configuration B. The misleading String 2 in Configuration C suggests a more direct solution as compared to the attached String 3. This illustrates that the probability of wrong choices is determined by the interrelationship of concurrent complementary relationships between actor, string and target suggested in a configuration. We agree with Richardson's expression that relative difficulty of Tasks A, B and C depend on the relationship between attached and detached strings. However, preferences must be predicted on the basis of differences in implied action consequences and not on the basis of string-target relations undependently from action. Without including action consequences, it is not clear why Configurations A and B differ in difficulty.

Table 5: Number of lower-order affordances to be integrated in order to realize the three suggested solutions for tool-use configurations A,B and C from Richardson (1932) respectively.

Configuration	String 1	2	3
A	1	1	1
B	2	2	2
C	2	1	2

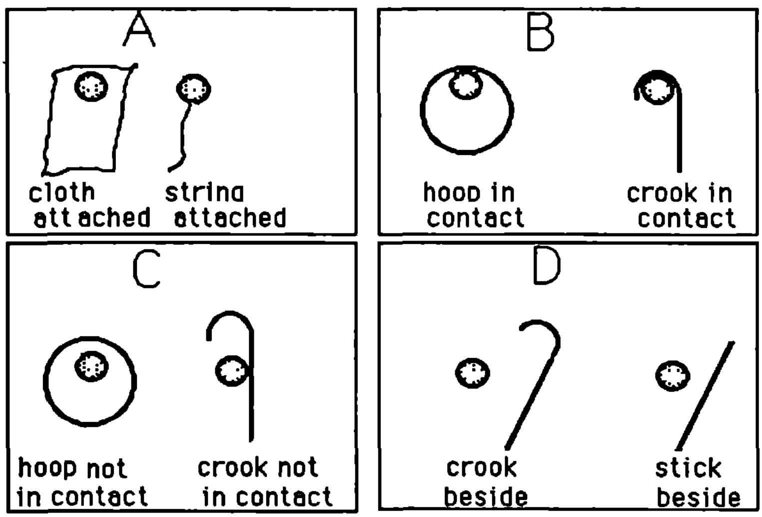

Figure 11: Tool use configurations according to Bates et al. (1980).

Köhler (1917) obtained a promising result in his experiments: a gap perceived between tool (a stick) and target (a banana out of reach) makes it difficult for these animals to "see" the function of the tool. Only after extended practice will the chimps perform this task whereas they do so spontaneously in the case of spatial contact between tool and target. Bates, Carlson-Luden & Bretherton (1980) have performed similar experiments with human infants and obtained comparable results. These authors have shown that babies between 40 and 44 weeks begin to perform tool-use tasks. They compared eight tool-use configurations in which a toy must be obtained with the aid of a tool (see Figure 11). Children perform best if the toy and the tool are attached (either a toy lying on a cloth or a toy with a string attached to it); a somewhat lower performance level is reached if the tool (a hoop or a hook) and the toy are in loose contact with each other; performance is worse if toy and tool are not in contact. Though the research of both Bates et al. (1980) and Köhler (1917) show the importance of spatial contact, they weren't able to clarify its precise role. Our experiments show that spatial contact is not helpful as such. Only if the spatial contact is needed for realizing the tool function does it facilitate the solution. From our theoretical description of affordance structures, we can now see why cloth and string attached are the easiest cases. These are the ones in which the relation between tool and target needed for the solution, is already realized. Moreover, the realization is safe against disturbance. Provided that too erratic movements are excluded, the actor actually should not be aware of the tool-target relationship and treat the cloth or the string as just a part of the target. We might call tool-use trivialized, here. Children developing their skills may begin to use tools in such trivial cases, extending their skills to the more difficult ones, requiring more specifity. Probably, the next step would than be the case of loose contact between crook or hoop and target. Also here, the required tool-target relationship is already realized, but it must be maintained so that the target follows a movement of the tool towards the child. Compared to the string/cloth example, the kind of the particular tool-target relationship must be recognized in order to anticipate a successful action. The necessity to control this relationship in action makes the affordance structure involved more complex. In the case of loose contact between target and crook or hoop, the required contact between tool and target at the right place must be anticipated. In the last example tools and target are completely detached so that the relationship of the two must be anticipated completely. The existence of such changes in complexity of affordance structures involved shows that developing tool use may be due to increasing perceptual differentiation. In the so called trivialized cases an actor doesn't need to differentiate the relational properties of tool and target in relation to an possible action. Demands on specifity and with it embeddedness of relational properties increase with increasing difficulty of tool-use configurations.

Summarizing, with the assumption of affordance structures it is possible to describe the increasing complexity of the tasks used by Bates et al. (1980). In these terms the role of spatial contact as embedded in action can be described explicitly.

Our reinterpretation of the results of Bates suggests that children seem to solve tasks involving less complex affordance structures earlier in development than the more complex ones. The examples given are reduced to tool use tasks for bringing something within reach. In order to explore if development of action may be characterized more generally by increasing complexity of the affordance structures involved, we analysed other kinds of manipulative actions. We used wellknown examples of actions that are described in the ordinal scales of psychological development in infancy by Uzgiris & Hunt (1975) as characteristic for cognitive development at certain stages. We will discuss whether the ordering corresponds to the one that could be obtained according to complexity with the aid of our criteria. In this manner, our description could be a diagnostic tool for characterizing infants and young childrens' cognitive development. The instrument used by Uzgiris & Hunt's (1975), and most, or all other diagnostic instruments are based on empirical criteria of what a child of a certain age is supposed to do, or know.

In some cases, the ordering of difficulty might seem obvious. Consider the following task: a mechanical toy car must be activated by winding it up by means of a key. The act of winding is modeled by an adult person. After playing, the child wants to reactivate the toy once more. Children 9 to 12 months of age solve this problem by a request for direct action on another person. The quite simple manipulatory action of handing the toy to another person is a substitute for the manipulatively quite complex action of winding the toy themselves. The younger children could therefore be said to use the mother as a tool. However, they do not need any detailed insight in how the "mother-tool" relates to toy and key. The action of giving is enough to realize the intended goal, to obtain a functioning toy.

Children 18 to 22 month of age attempt to activate the toy by using the key as tool. How they can handle the key depends on how it is grasped. But as a consequence of how the key is intended to function, further constraints on action follow from the relational mechanical properties of key and lock. These constraints, as well as additional ones resulting from their combination must be met in order for the child to reach the goal.

The preceding description can straightforwardly be translated into an outline of the complementary relationships involved between child, toy and mother for the younger children and between child, toy and key for the older ones. This may already suffice to illustrate the difference in complexity between the affordance structures involved in the actions of the younger and those of the older ones (see Figure 12).

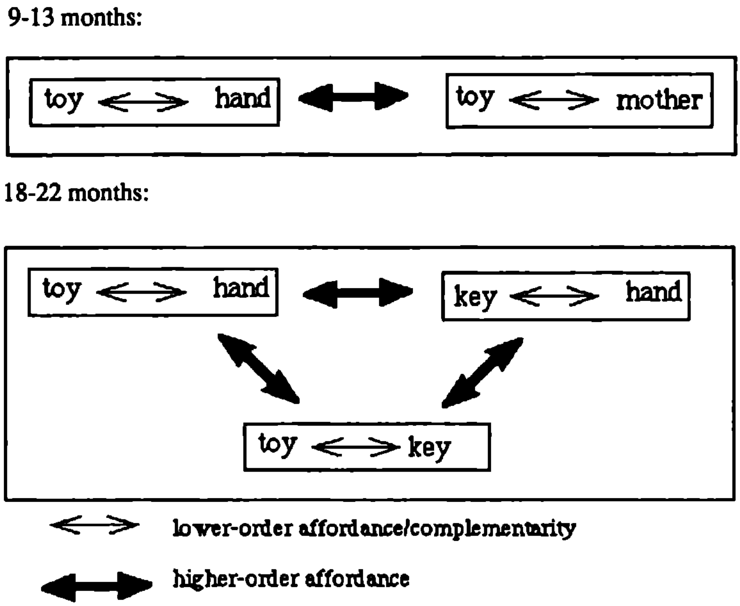

Figure 12: Affordance structures involved in different ways for getting a mechanical toy car activated at the ages of 9-13 months and 18-22 months respectively.

But also in somewhat less obvious cases, our discription might be put to work: 9-12 months old children are able to put small objects into clearly wider containers. But they fail in form board tasks were an object must be fit to a narrow opening of the same shape. Yet, both these actions realize a containment relation. Differences become visible only by analyzing the complementary relationships between the respective elements of the action.

In the case of a little object into a big container, the action is constrained by the global size relationship. The act of grasping the object is not constrainted by the act of putting the object into the container. In order to solve this problem, a sequence of actions must be anticipated (in our words, a diachronous integrated affordance structure must be perceived): first the actor-object relationship of grasping must be realized; second the object must be transported towards the container; and third the object must be put into the container. For this, the object must be above the container, no matter in which orientation.

By contrast, in the case of the form board, exact adjustment of the object's orientation to the shape of the opening is required. This means that there is much more, synchronous, temporal integration in the affordance structure. The act of orienting the object is constrained by the symmetry axes of the shape.The number of ways could vary, in which in the last stage of the action the adjustment of the shape's orientation could be realized. The alternative ways to do this increase with the number of symmetry axes of the shape. Thus the simplicity of the shape, in terms of symmetry axes, relaxes the constraints on the planning and anticipation of the task. Therefore, the task will be easier if the object and the opening are more symmetric. In this way fitting a ball into the opening of the formboard is much easier than fitting a bar to the respective opening. In terms of affordance structures this means the following: anticipating the act of orienting the object consists of more complementary relationships between specific properties of the object and specific properties of the grasping system if there are less symmetry axes. See Figure 13 for a comparison of the integration demands of fitting a small object to a large container and one example for a form board task concerning a bar as object.

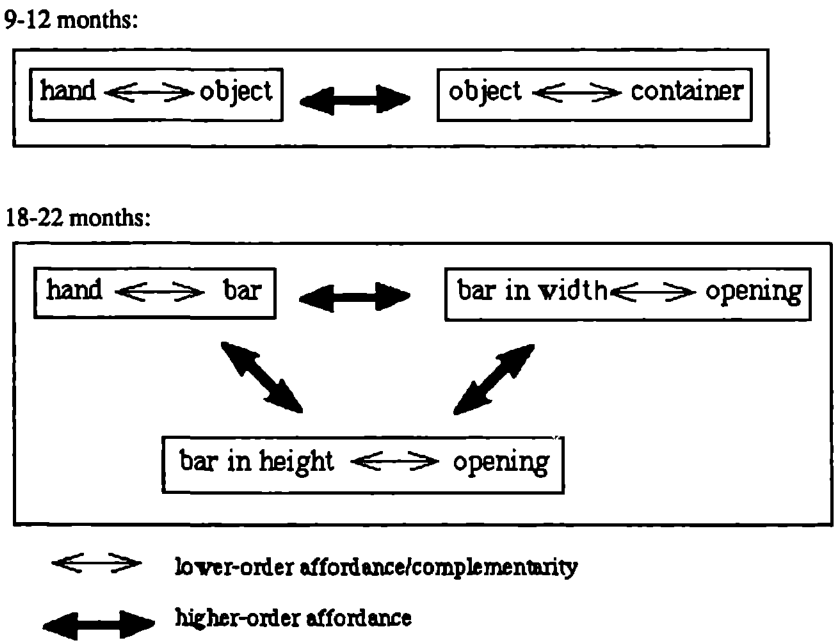

Figure 13: Affordance structure involved in fitting a small object to a big container and a form board task performed by children of 9-13 months and 18-22 months respectively.

Complexity of affordance structures involved in solving the manipulative tasks mentioned seems to provide predictions of their relative difficulty. Development in manipulation of objects can be described in terms of increasing differentiation of relational properties of actor and different objects and their embedding in action.

General Discussion

In our earlier work, a description of higher-order structures of complementary relationships that could exist between actor and environment (affordance structures) was proposed. These must be perceived in order to realize complex forms of action such as tool use. Theoretical sources of complexity were proposed. These regard the nature of the temporal and structural integration demands of the affordance structure; the way different complementary relationships between actor and environment are joined together. The observed difficulty of our tasks corresponds to these sources combined.

Our present experiments show that the consequences of affordance structure complexity are consistent over age groups and tasks. With respect to age groups, the older groups are able to deal with more complex affordance structures than the younger ones. But more importantly, the complexity of the affordance structures determines not only the behaviour of the younger children, who are in the process of learning to use tools. But the complexity is also mirrored in the behaviour of the older ones. Whereas for the younger children higher integration demands lead to failure to perform the task, the older ones prefer a mode of performance that requires a less complex affordance structure.

It was illustrated in our experiments that the complexity of affordance structures could be used successfully to predict the preferred realizations for different tasks. From an analysis of different manipulative tasks we argued for the ecological validity of these concepts. The tasks younger children are able to perform in our terms are less complex than the ones only older children can do. A possible application could be a diagnostic instrument for characterizing infants and young childrens' perceptive/cognitive development. At present, many diagnostic instruments are selected by means of empirical criteria of what a child of a certain age is supposed to do, or know. We might now be able to develop criteria to determine why certain tasks work well as diagnotiscs and others don't, and therefore ultimately to systematically devise certain tasks.

In our analyses, we have implicitly assumed that our description could be applied for different response measures. Although we have provided no direct evidence for this assumption, the general applicability of our theoretical description might be taken as indirect evidence for it. We may therefore propose our higher-order affordance structure concept as a means to analyze possible forms of action according to their complexity.

The validity of our description accross age groups and tasks suggests that development in a perception-action perspective could be described by means of affordance structures. Development then would be characterized by the ability to deal with affordance structures of increasing complexity. This view corresponds to the notion of development as a process of differentiation as e.g. expressed by Werner (1957) or in the field of perceptual development by E. Gibson (1988). She points out that "progressive differentiation results in increasing specifity of correspondence of perception with sources of stimulation in the environment" p.4. "Perceptual development seems to proceed toward finer differentiation of embedding in events and at the same time progressive realization of superordinate relations" p.17. The emergence of tool use during the second year of life is, in these terms, the result of a more general ability to perform nested actions subservient to a superordinate goal. In order to discover tool functions, properties of objects are to be differentiated specific to actor and target. Our description provides an account of what kind of embedded structures are to be perceived in order to do this. The increasing specifity of the perception-action couplings needed to act efficiently is expressed in terms of mutual constraining affordances, i.e. in terms of embedding.

Our approach fits attempts to characterize growth e.g. (van Geert, 1991) and development (Thelen, Kelso & Skala, 1987) in terms of a self-organizing dynamic systems. An interesting property of the behaviour of many dynamic systems is their so-called scale invariance; the emergent properties of the system at micro level are similar to those on macro level. This means that for the analysis, the elements are arbitrary. In our tool use task the elements were the grasping system as a whole, a tool and a toy. We assumed that this perception/action repertoire was already available to the child. Children actually perform these movements. If the movements themselves are the focus of analysis, a finer grain of description becomes necessary. On the next finer grain the elements could be individual joints and limbs of the actor, and similarly detailed components of tool and target. The next coarser grain of analysis to the present one could be the social interaction, described in terms of verbal and non verbal communication during task performance. Also here it is possible to describe affordances of different actors, tool and target and their interaction. Which level(s) of description are chosen depends on the focus of research.

We must take care, however, not to confuse our description with a theory of development. The principles that drive the increasing differentiation, in our terms, are still unspecified. In order to discover those principles, the description should be used in a *dialectical* approach to development. In such an approach developmental outcomes are treated as dynamic interaction between different dimensions from biological up to cultural-historical level. Conflict within and between those dimensions are assumed to be the source of development (see Hopkins & Butterworth, 1990, p.21). Because the complexity measure of affordance structures is not specific to task or age, our description could provide an instrument for describing action on different levels as respective organism environment relationships. Given that the validity of our concept could be established more firmly than possible in the context of this paper,the description of affordance structures could be a possible instrument to set a step in realizing the claim of Hopkins & Butterworth " to define the critical aspects of the organism-environment relationship that are important at different points in development" (p.27).

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EPILOGUE

Epilogue

The existence and use of tools is a product of environmental circumstances and action combined. Therefore the branches of science that deal with environment or action should develop a common language to approach the problem of the relation between them. The emergence of tool use cannot be studied from a psychological point of view exclusively, but neither can it be excluded. The value of the present, psychological, description of tool use in terms of affordance structures should be assessed in the context of other disciplines like ethology, archeology and cultural anthropology. Psychologists could provide e.g. for archeologists a criterion for what type of environmental structures possess significance for a certain action. Man-made tools thus could be classified according to complexity of their affordance structures. Since the complexity could be taken as a measure of human development, archeologists could use this measure for the same purpose on a filogenetic scale.

Ethologists have argued that tool use is all but exclusively reserved for humans. In their view, not only our direct ancestors, the prehuman primates, but even invertebrates, fishes, birds and other animals are able to use, or even manufacture tools (Beck, 1980). One could argue that this is a matter of definition. This makes sense, as there is no generally agreed-upon definition of the concept of tool. Therefore, there is no theoretical criterion for distinguishing tool use from other forms of action. The psychology of tool use could provide a diagnosis. It could be proposed to distinguish actions according to their complexity, in terms of their affordance structure. It may turn out that instance of tool use are found to be dispersed over a wide range of complexity. This may cast doubts on efforts to obtain a single, satisfactory definition that covers all possible instances.

In the preceding chapters, an attempt was made to contribute to the ecological approach to perception, a demonstration of how complex action could be dealt with in this framework. The application of the affordance structure concept to a broader range of actions could its relevance for perceptual development. Therefore, a future task would be to apply the concept to actions that precede, accompany and follow tool use. An application seems possible to manipulative tasks that contain less complex affordance structures than tool use, e.g. those which encompass relations of containment or support between objects. Instances of such tasks are putting things into a container or building a tower.

A comparison of the tool use actions with those of similar complexity in other domains such as exploration, social interaction and speech would be of interest. For an

illuminating survey, see Greenfield (1991). In her view, like ours, these actions have in common a requirement for integration of a hierarchical structure of events.
Manipulative actions that require affordance structures of higher complexity than tool use are e.g. those of tool making. An object must be transformed into a tool before it can be used. This requires a principally deeper nesting of actions than just for tool use.
In sum, the study of tool use from a psychological point of view could provide insights in the development of perception as well as in the nature of tools. The present work provides a challenge rather than a task fulfilled, for me and, I hope, for others as well.

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SUMMARY

Summary

In order to bring tool use within the scope of ecological realism, it was necessary to deal with some conceptual issues of ecological realism first. Whereas ecological realism takes body-scaled information as its starting point, in the case of tool use object-scaled information has to be considered as well. In order to perceive the function of a tool and to realize its function in an action, the proportions and mechanical characteristics of the tool have to be viewed in reference to the actor *and* to the object(s) which are the target of the action. A skrewdriver, which has both an object-scaled and a body-scaled ending may serve as illustration. In the ecological approach until now, body-scaled information belongs to the affordance concept, which has an intimate relation to action. Object-scaled information was studied in the context of event perception in which the perceiver has the role of an observer. For tool use, object-scaled information has to be incorporated in action. Action becomes an actor-involving event. Thus thee study of tool use required closure of the gap between event perception and action.

Another distinctive aspect of tools is that they are a means to an end. Their function is subordinated to the goal of the action. The subordination has a structural and a temporal aspect. Structurally, the to be realized actor-target relation prescribes the required actor-tool complementarities. Affordances of tools contain a nested structure of complementary relationships between actor and environment and between objects in the environment. In order to realize the goal of the action, however, these complementarities must be placed in an appropriate temporal organization. Whatever has to be realized first is subordinated to the goal which is realized last. Therefore an actor on a global level has to envisage the event in its entirity.

Tools provide an empirical reference point in the issue of relationalism versus realism for the ecological approach. Realism requires a fully determined world in which affordances exist as objectively given entities that cannot be changed by a perceiver's intentions. Tool artefacts, however, are a clear example for how the affordances of the environment can be changed. Tools extend both, the environmental resources to be used in action, and the action capacities of those who use them. Relationalism allows the study of how organism and environment co-develop. Therefore preference was given to an exclusively relational approach of tool use.

In order to describe how body-scaled and object-scaled information are integrated in perception, the notion of higher-order structures of complementary relationships was introduced (affordance structures). These are perceived in order to realize complex forms of action such as tool use. Affordance structures vary in complexity. Two sources of complexity were identified, corresponding to the earlier mentioned structural and temporal integration demands, respectively. The complexity was assumed to be a

determinant of the difficulty of tool use tasks. To test this prediction, a variety of tasks was employed, all of which resembled Köhler's (1921) paradigm. In his experiments, a chimpanzee had to use a stick as tool in order to obtain a banana. In the experiments presently discussed, the stick is replaced by a hook (though it sometimes was used as a stick), the banana by a desirable toy, and the chimpanzee by a young child. We varied the relative spatial positions of the tool and target to obtain tool affordances of different complexity. Also, task, instruction and children's age was varied. The observed difficulty of our tasks agreed well with the predictions.

In follow-up studies, the effect of affordance structure complexity was consistent over age groups and tasks. With respect to age groups, the older groups were able to deal with more complex affordance structures than the younger ones. But more importantly, the complexity of the affordance structures determined not only the behaviour of the younger children, who are in the process of learning to use tools. Also the older ones were influenced by the complexity. Whereas for the younger children higher complexity lead to failure to perform the task, the older ones preferred a mode of performance that requires a less complex affordance structure. It was illustrated by an analysis of different manipulative tasks that generally, younger children are able to perform possess less complex tasks than older ones. On this basis the ecological validity of these concepts was argued for.

The validity of our description accross age groups and tasks candidates it for an account of development in a perception-action perspective. Development then would be characterized by the ability to deal with affordance structures of increasing complexity. This view is in accordance with the notion of development as a process of differentiation as e.g. expressed by Werner (1957), or by E. Gibson (1988) in the field of perceptual development. The emergence of tool use during the second year of life is, in these terms, the result of a more general ability to perform nested actions subservient to a subordinate goal. In order to discover tool functions, properties of objects are to be differentiated specific to actor (body-scaled information) and target (object-scaled information). Our description provides an account of what kind of embedded structures are to be perceived in order to perform nested actions.

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SAMENVATTING

Samenvatting

Om werktuiggebruik vanuit het perspectief van het ecologisch realisme te kunnen benaderen, moesten allereerst de uitgangspunten van deze benadering aan een kritisch onderzoek worden onderworpen. Dit betreft de aanname dat hetgeen in de omgeving van een actor van belang kan zijn, in relatie moet worden gezien met proporties en dimensies van de actor zelf. Echter, bij werktuiggebruik spelen eveneens de relatieve proportie en dimensionering van voorwerpen onderling een rol. Een werktuiggebruiker moet zowel letten op de relatie tot het eigen lichaam, als op die van de voorwerpen onderling. Ter illustratie: één van de uiteinden van een schroevendraaier heeft een proportie die complementair is t.o.v. de actor (het handvat); de ander een proportie die hem complementair maakt t.o.v. de schroef.

In het ecologisch realisme is de relatie tot het lichaam ondergebracht in het concept *affordance*. Een *affordance* heeft een directe betrekking tot mogelijke actie. De relaties van objecten tot elkaar wordt binnen het ecologisch realisme onderzocht binnen het domein van de waarneming van gebeurtenissen. Maar hierin heeft de de waarnemer slechts de rol van toeschouwer. Bij werktuiggebruik moet deze soort van informatie gekoppeld worden aan de mogelijkheid tot actie. Daarom moet het onderzoek naar werktuiggebruik de kloof overbruggen tussen de waarneming van gebeurtenissen en actieve participatie hieraan.

Een andere distinctieve eigenschap van werktuigen is, dat zij middel tot een doel zijn. Hun functie wordt bepaald door het doel van de handeling. Relaties tussen actor en werktuig en tusssen doelobject en werktuig staan ten dienste van de mogelijkheid van een relatie tussen actor en doelobject. Deze ondergeschikteid heeft zowel structurele als temporele aspecten. Wat het structurele betreft, de gewenste relatie tusen actor en doelobject legt vast welke relaties tussen werktuig en actor, alsmede tussen werktuig en doelobject van belang zijn. Maar om het doel te realizeren, moeten deze tevens in een adequate temporele organisatie worden geplaatst. Wat als eerste moet worden uitgevoerd, is ondergeschikt aan een doel dat pas als laatste wordt gerealiseerd. Daarom moet de actor de handeling van tevoren globaal kunnen overzien.

Werktuigen zorgen voor een empirische inbreng in de discussie betreffende relationalisme versus realisme binnen de ecologische benadering. Realisme veronderstelt een kant en klare wereld, waarin de affordances bestaan, onafhankelijk van het doen en laten van de waarnemer. Maar het ontstaan van werktuiggebruik zorgt juist voor uitbreiding, zowel van de aanwezige mogelijkheden van de omgeving, als van de handelingscapaciteit van de gebruiker. Relationalisme maakt het mogelijk de

ontwikkeling van individu en omgeving in hun samenhang te bestuderen. Daarom werd in deze studie de voorkeur gegeven aan een relationele aanpak.
Om te beschrijven hoe de waarneming de integratie aanbrengt tussen aan het lichaam en aan andere objecten gerelateerde informatie hebben wij het begrip van een hogere-orde structuur van complementaire relaties ingevoerd, de zg. affordance-structuur. Affordance structuren dienen te worden waargenomen ten behoeve van complexe handelingen, zoals werktuiggebruik. Affordance-structuren varieren in complexiteit. Twee bronnen van complexiteit werden geidentificeerd, samenhangend met de eerder genoemde structurele- en temporele integratie aspecten. De complexiteit wordt gezien als een factor die de moeilijkheidsgraad van werktuiggebruik bepaalt.
Om deze voorspelling te testen is een aantal werktuigtaken ontwikkeld, die gebaseerd zijn op Köhlers (1921) aanpak. In zijn experimenten moesten chimpansees een banaan binnen handbereik halen met behulp van een stok. In de onderhavige experimenten is de stok vervangen door een haak (die trouwens soms als stok werd gebruikt), de banaan als doelobject door een gewenst speelgoed, en de aap door een jong kind. De positie van de haak ten opzichte van het doelobject werd systematisch gevarieerd om affordance structuren van verschillende complexiteit te verkrijgen. Taak, instructie en leeftijd werden eveneens gevarieerd.
De geobserveerde moeilijkheid van de taken kwam goed overeen met de voorspelde. Complexiteit van een affordance structuur heeft een consistent effect over verschillende taken en leeftijden. Oudere kinderen kunnen complexere structuren aan dan jongere. Maar wellicht belangrijker is, dat de complexiteit van deze structuren niet alleen het gedrag van de jongere kinderen beinvloedde, maar ook dat van de ouderen. Waar bij jongere kinderen een complexe affordance structuur tot meer fouten leidt, leidt dit bij oudere kinderen tot een een geringe preferentie voor de betreffende handeling.
Een analyse van verschillende manipulatieve taken liet zien, dat de volgorde waarin kinderen deze taken leren afhankelijk is van de complexiteit van de affordance-structuren. Hierop berust de ecologische validiteit van dit onderzoek.
De validiteit van onze beschrijvingswijze over verschillende leeftijdsgroepen en taken suggereert dat hiermee ontwikkeling kan worden beschreven in een perceptie-actie perspectief. Ontwikkeling zou aldus worden gekarakteriseerd als toename in de complexiteit van de waargenomen affordance-structuren. Deze opvatting stemt overeen met die van Werner (1957) of met die van E. Gibson (1988) in het domein van perceptieve ontwikkeling. De opkomst van werktuiggebruik in het tweede levensjaar is, in deze termen, het gevolg van een meer algemene vaardigheid tot het hierarchisch struktureren van handelingen ten dienste van een overkoepelend doel. Om werktuigfuncties visueel te detecteren moeten eigenschappen specifiek voor de actor-werktuig en de werktuig-doelobject relatie worden samengebracht ten dienste van een

actor-doel relatie. Onze beschrijvingswijze levert een middel om te laten zien, hoe dergelijke geneste relaties ten dienste staan van evenzeer geneste handelingen.

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Curriculum vitae

De auteur van dit proefschrift werd geboren op 14 april 1959 als tweede dochter van Ruth en Heinz Winkler te Oppach in de voormalige DDR. Na de achtjarige basisschool in Löbau te hebben afgesloten bezocht zij de zogeheten "Erweiterte Oberschule" alwaar zij na vier jaar met het "Abitur" (eindexamen te vergelijken met Atheneum B) behaalde. Vanaf 1978 studeerde zij te Leipzig Psychologie aan de Karl-Marx-Universiteit. Na deze studie werkte zij aldaar van 1983 tot 1986 als wetenschappelijk onderzoeker op het gebied van de visuele waarneming. Van 1987 tot 1992 was zij als AIO werkzaam bij de vakgroep ontwikkelingspsychologie aan de Katholieke Universiteit Nijmegen. Sindsdien bekleed zij een funktie als wetenschappelijk medewerker aan de "Kinderklinik des Inselspitals Bern", Zwitserland.